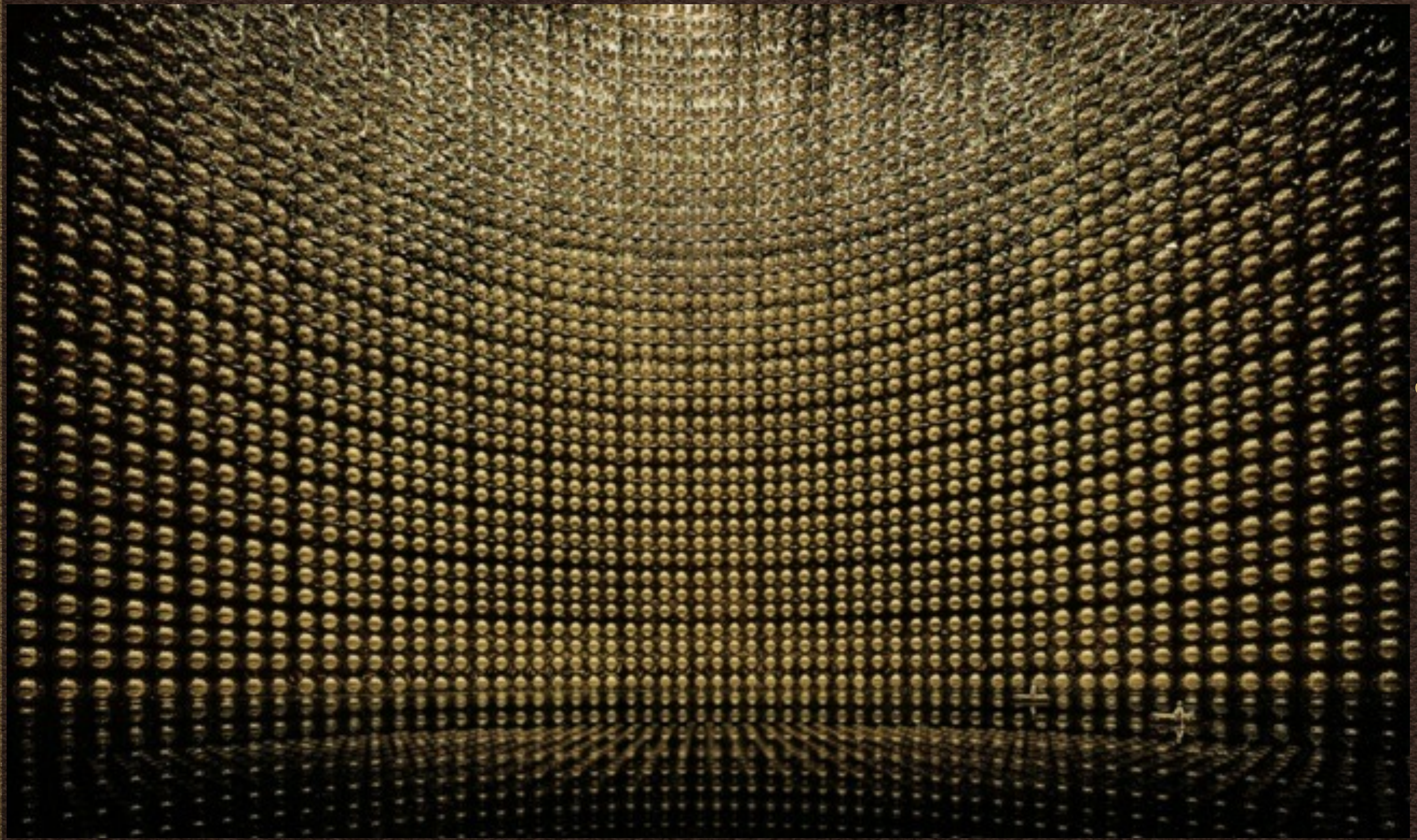
Super and Hyper-Kamiokande

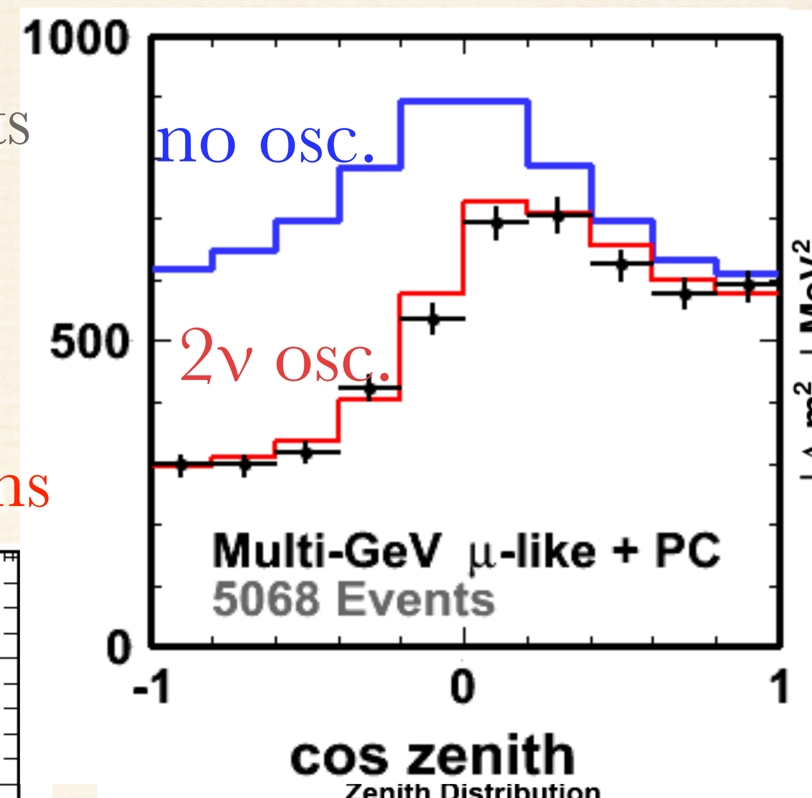


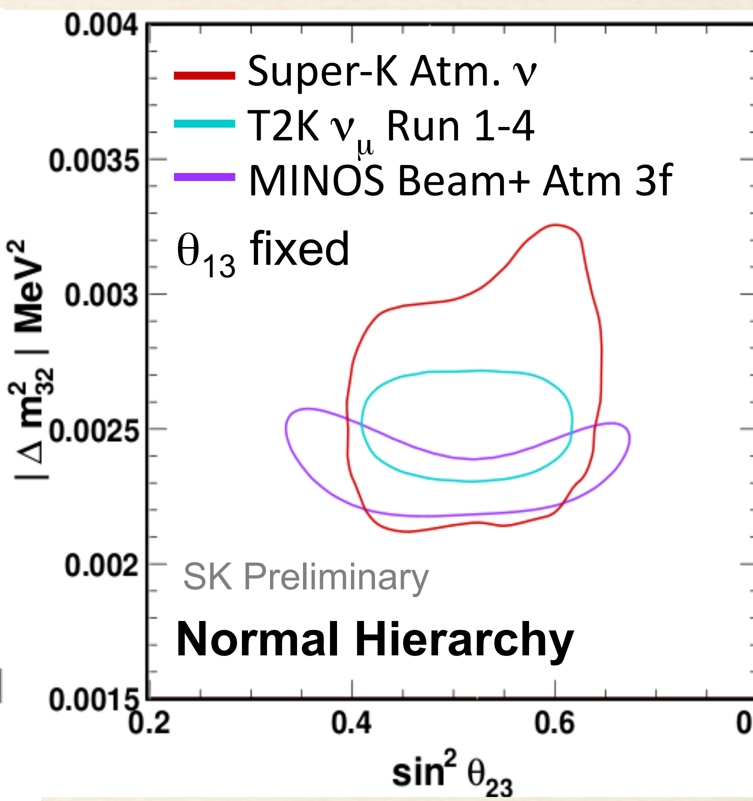
WINP Brookhaven National Laboratory
February 5th 2015

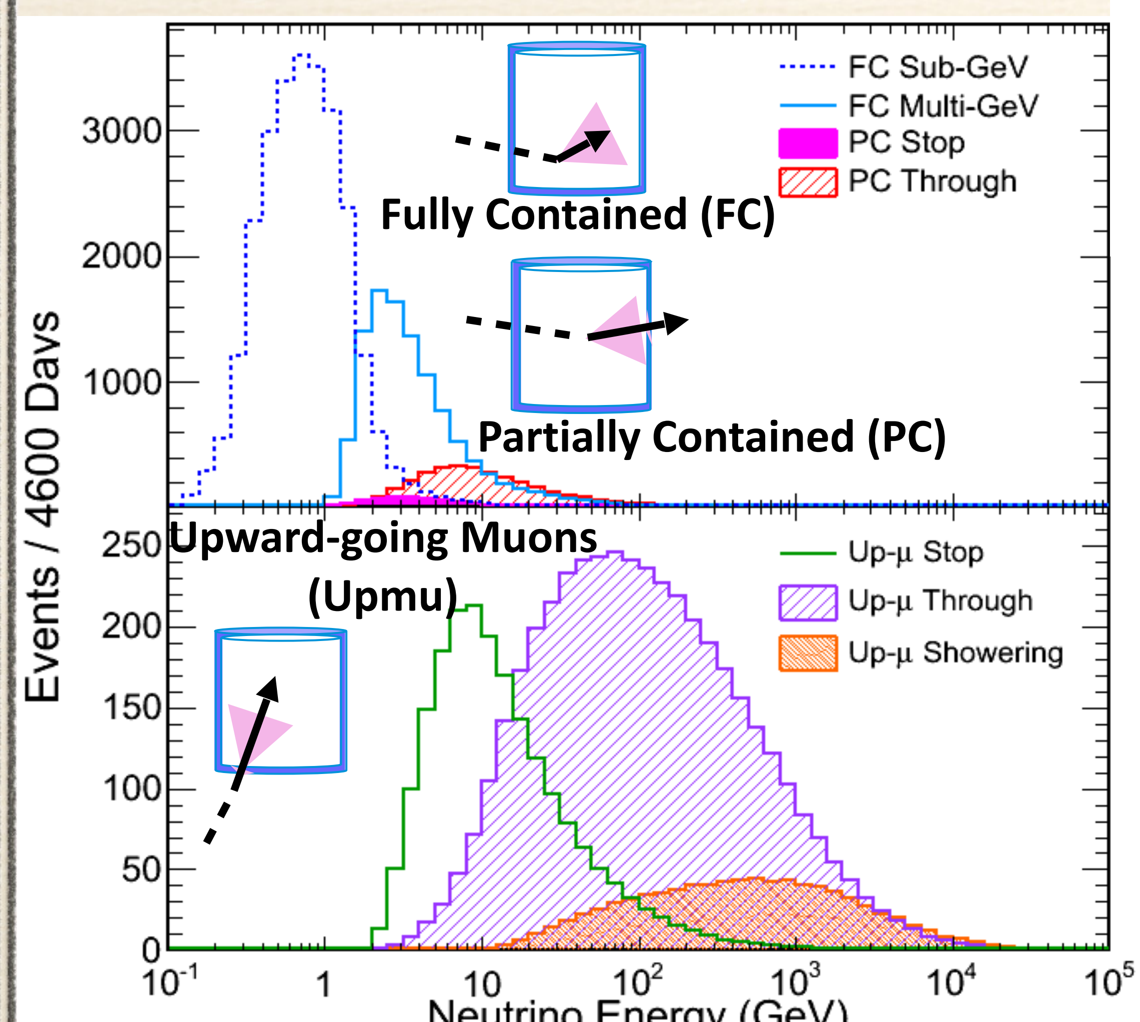
Michael Smy

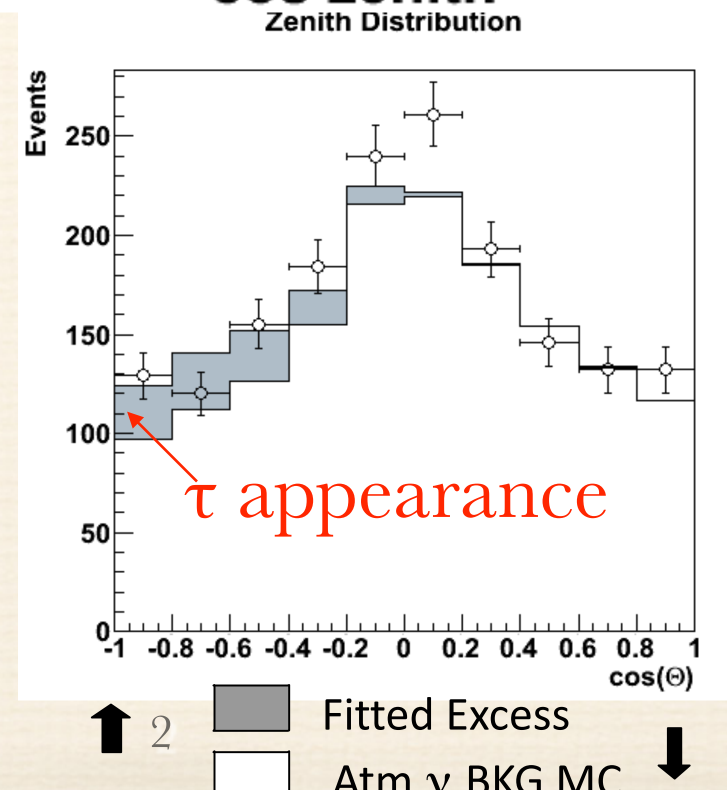
Super-K Results with Atm. ν's

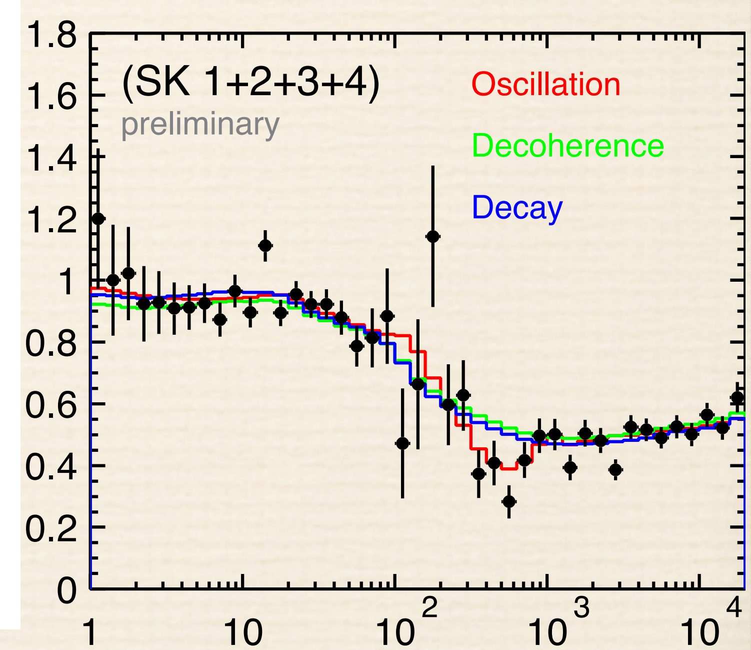
- θ_{23}, Δm^2_{32}: confirmed by long baseline accelerator experiments
- ν_τ appearance
- oscillation pattern (L/E)
- constrain sterile ν's, LIV, etc.
- large statistics: many subdivisions







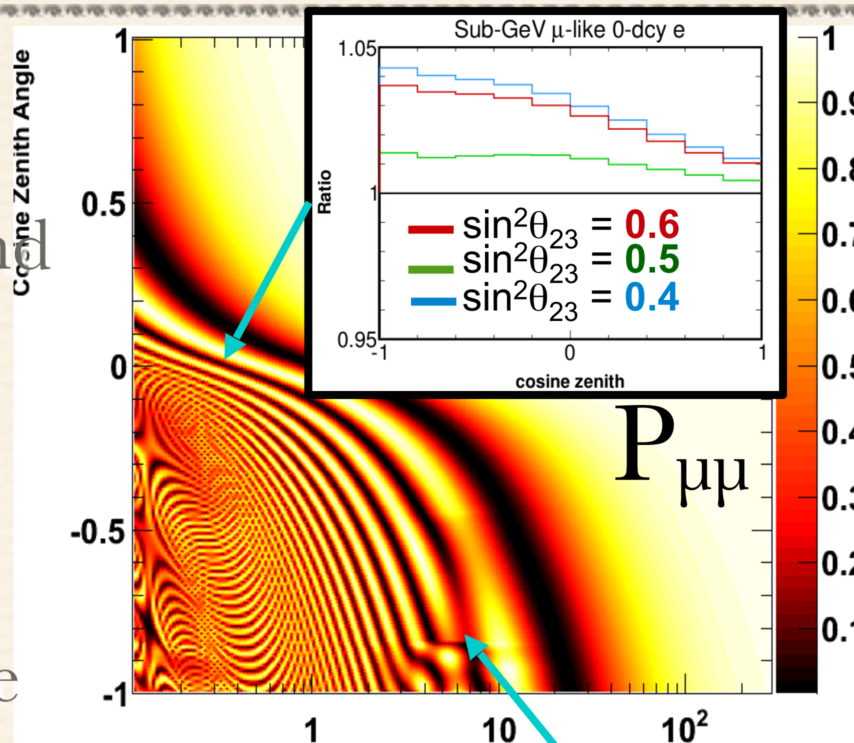




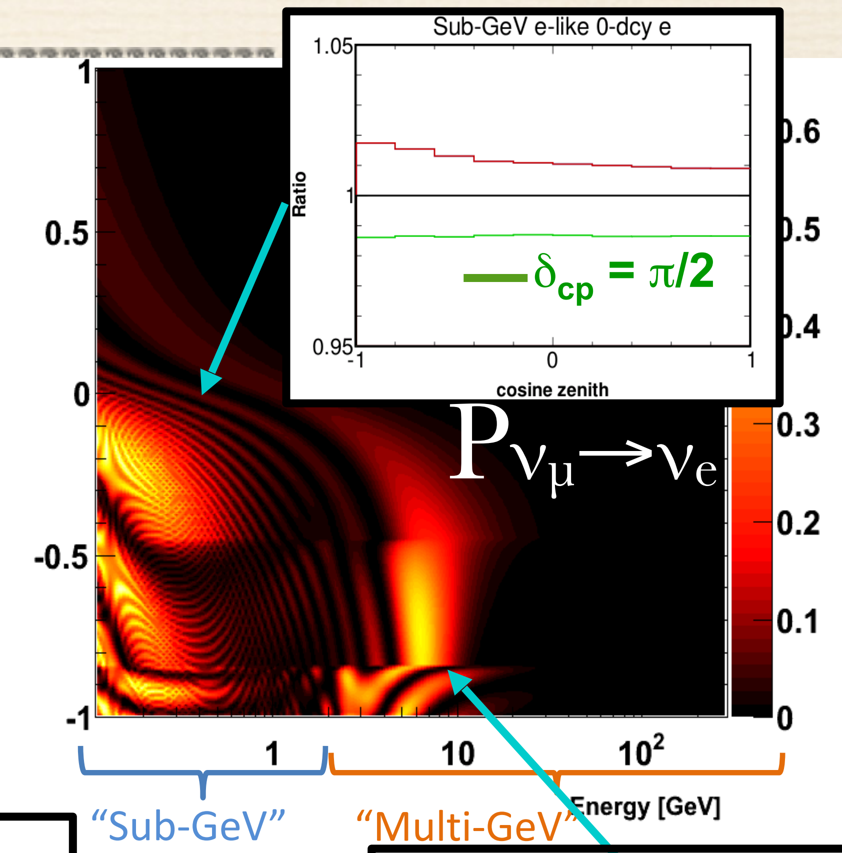
Full 3-Flavour Description

- fixed θ_{13} uncertainties
- resonance magnitude depends on hierarchy and 2-3 mixing (~½ appearance in IH)
- 19 sub samples: multi-GeV e-like samples divided into ν- and ν-like to check subdominant contribution $\nu_\mu \rightarrow \nu_\tau$ oscillation (e.g. ν_s, LIV)

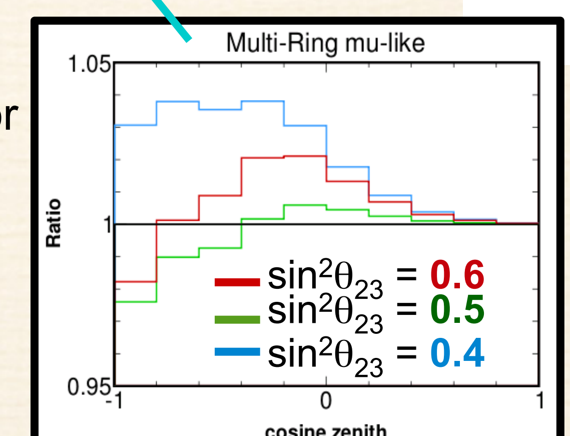
~10 km

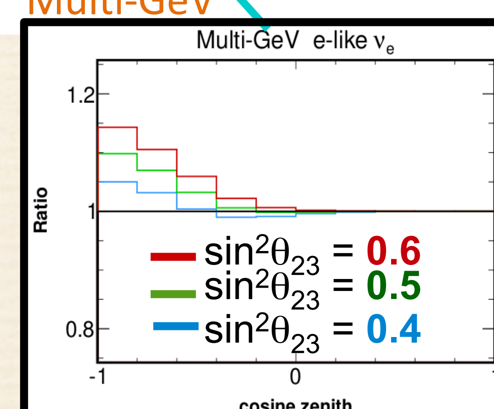


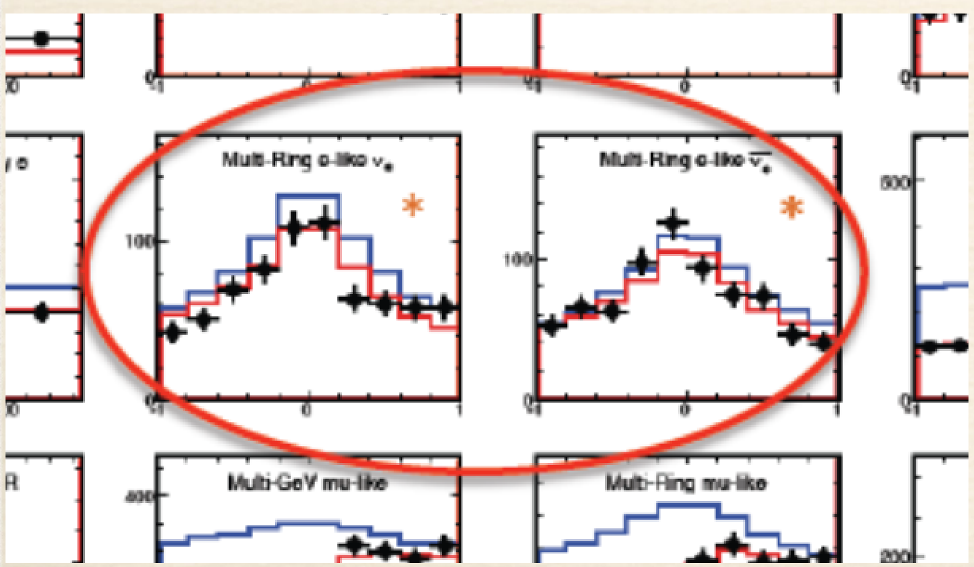
~10,000 km



Ratio to two-flavor oscillations

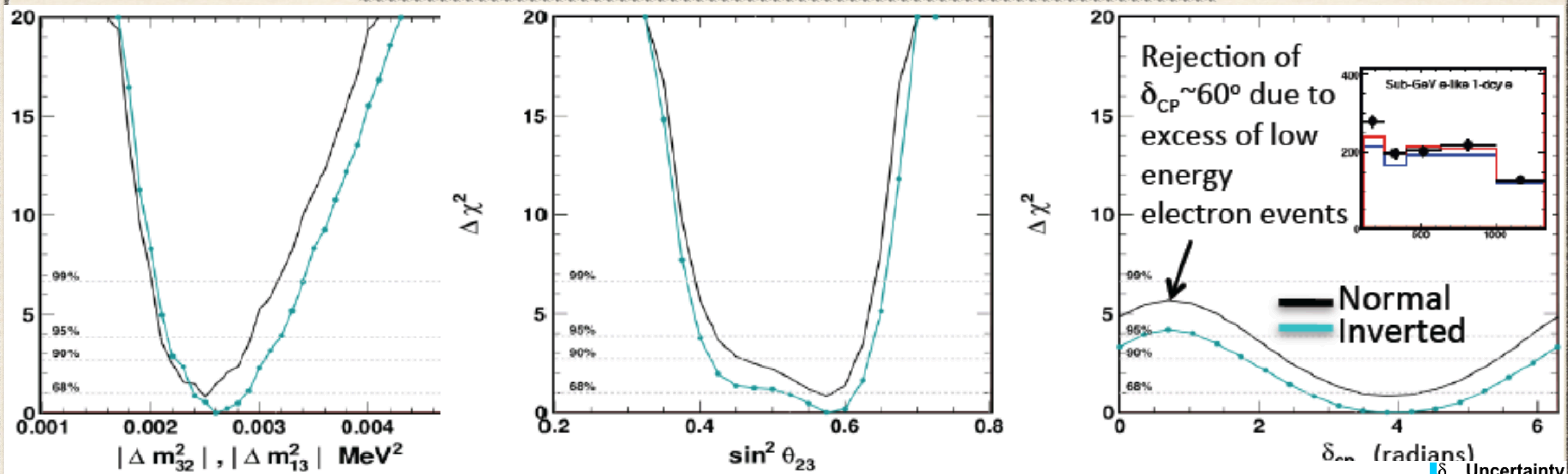






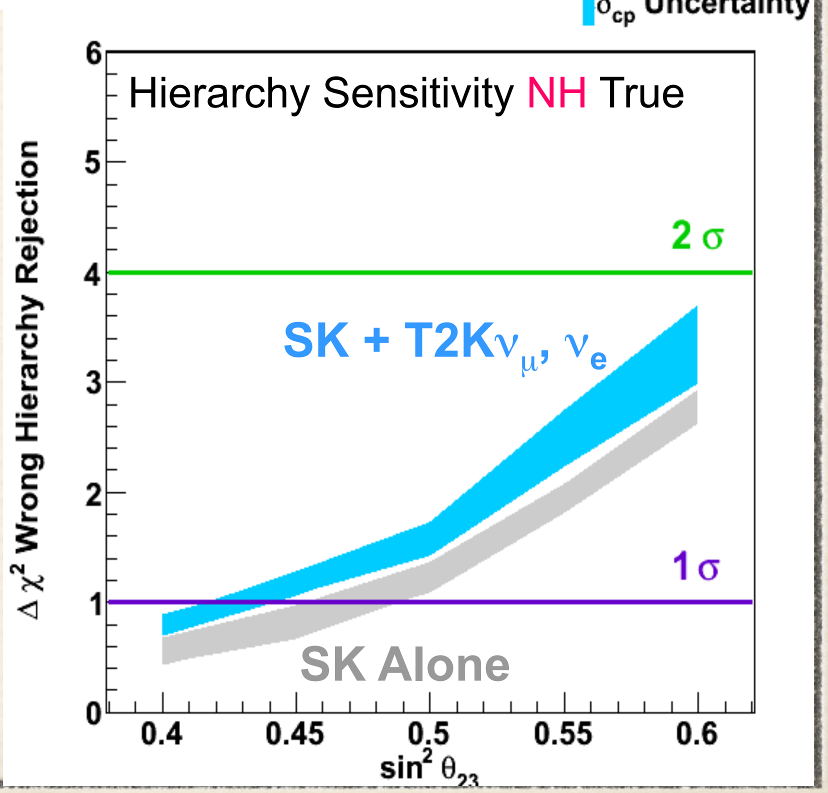
Purity	CC ν_e	CC ν_μ	CC ν_τ	NC
ν-like	69%	7%	11%	11%
ν-like	56%	8%	18%	17%
other	21%	34%	22%	22%

Super-K/T2K Analysis (fixed θ_{13})

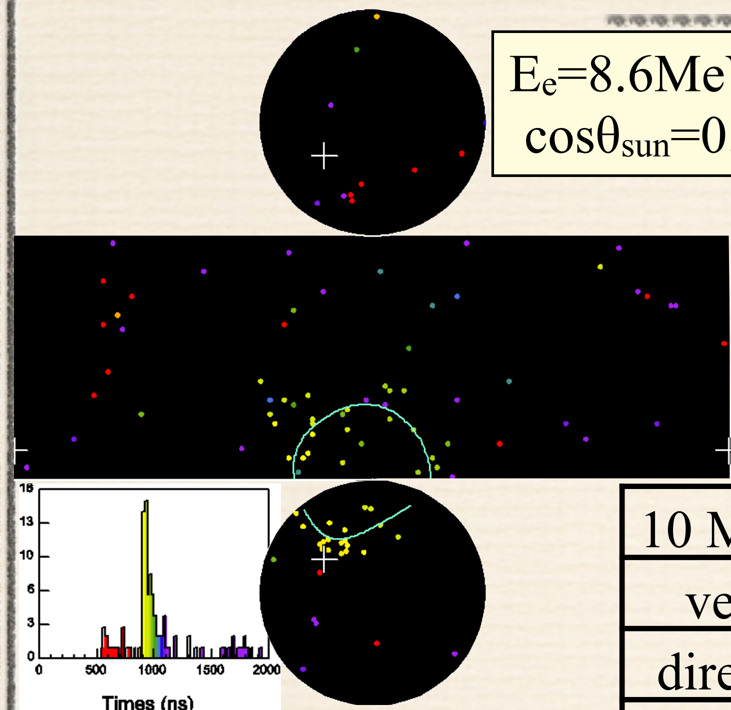


- weak preference for normal hierarchy (~1σ)
- sin δ_{CP}=0 allowed at 90% for both hierarchies

Fit (517 dof)	χ^2	θ_{13}	θ_{23}	δ_{CP}	Δm^2x10^{-3}
SK (NH)	559.8	0.025	0.57	3.84	2.6
SK(IH)	560.7	0.025	0.57	3.84	2.5
SK+T2K (NH)	578.2	0.025	0.55	4.19	2.5
SK+T2K (IH)	579.4	0.025	0.55	4.19	2.5



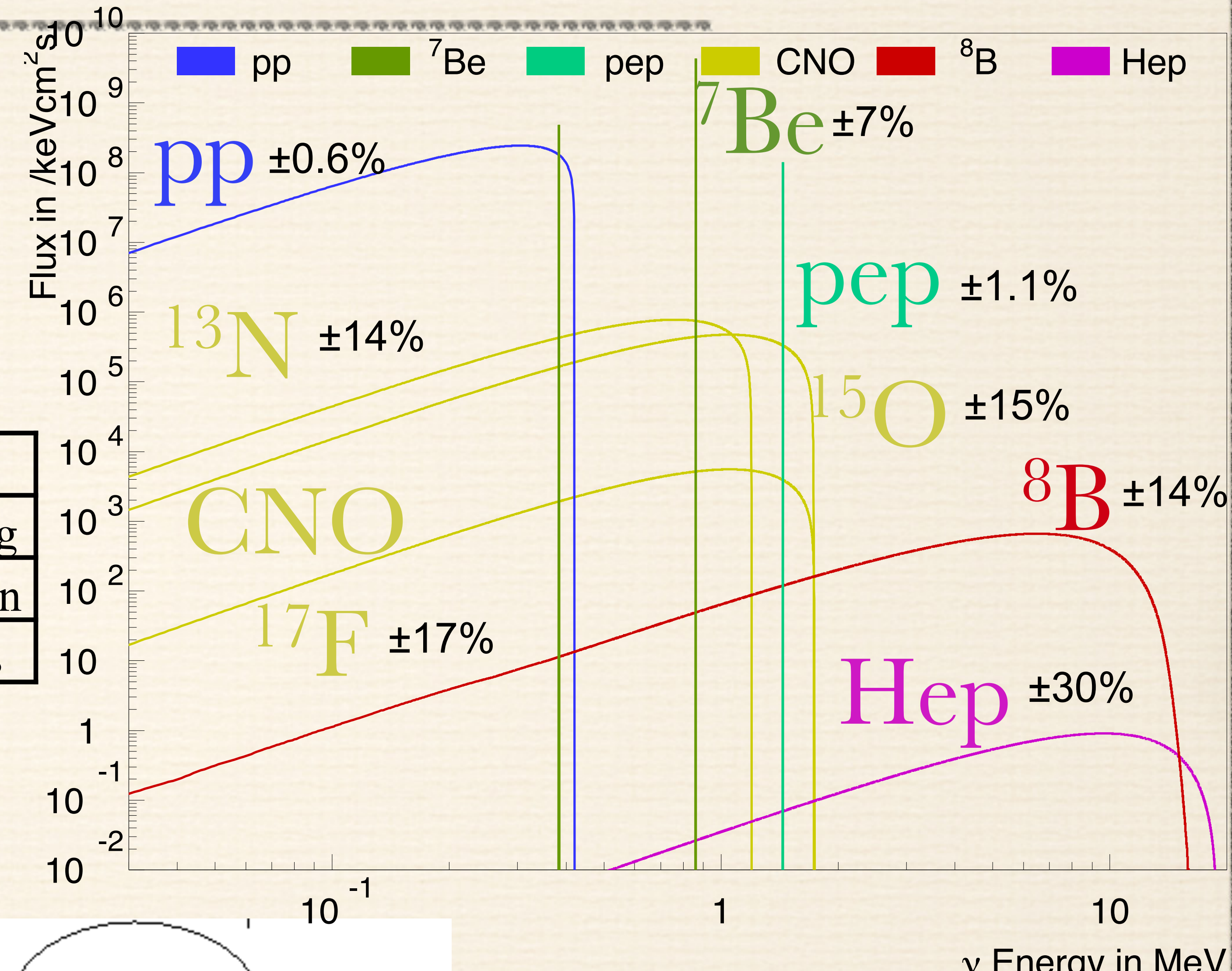
Super-K Solar Neutrinos

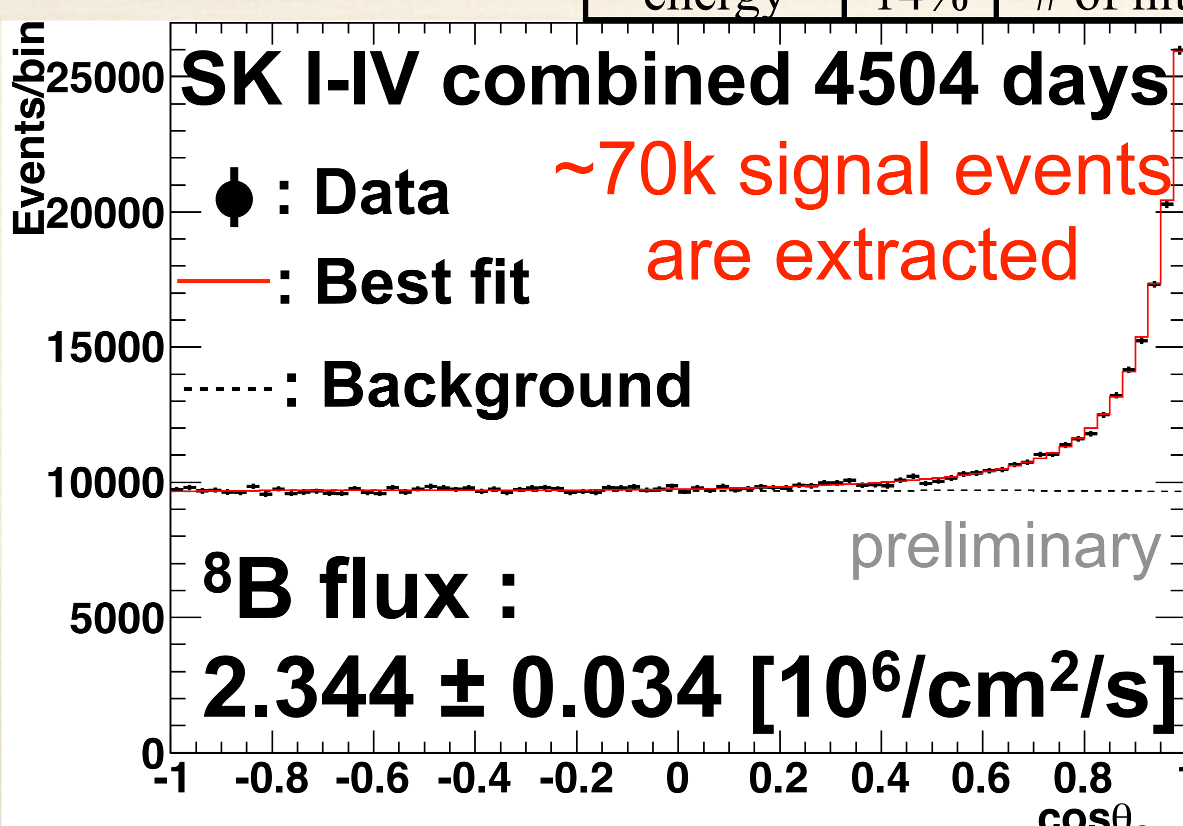


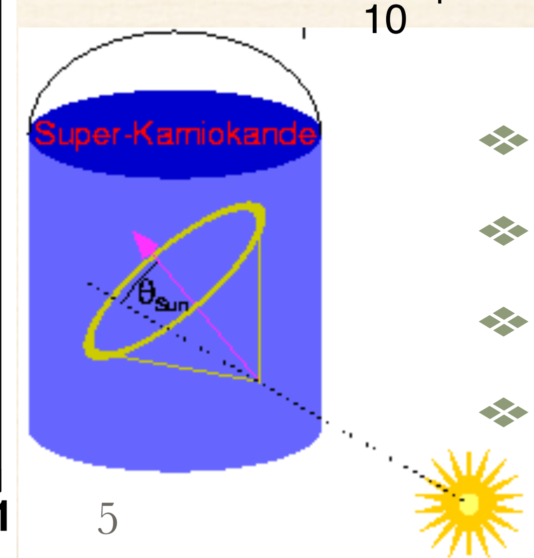
E_e=8.6MeV$_{kin}$
$\cos\theta_{sun}$=0.95

^{8}B solar ν's detected via ES: **ν+e⁻→ν+e⁻**
~ 6 hits/MeV
calibrated by LINAC and DT to 0.5%

10 MeV e⁻	resol.	using
vertex	55cm	hit timing
direction	23^0	hit pattern
energy	14%	# of hits



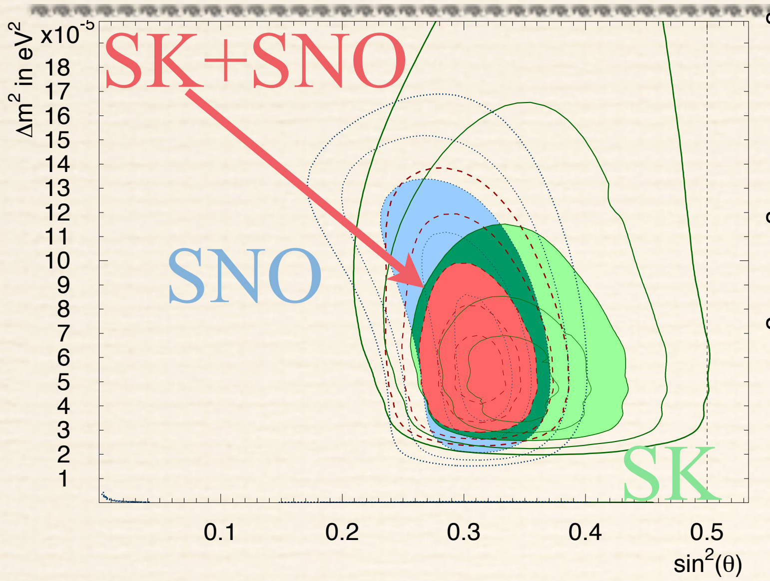


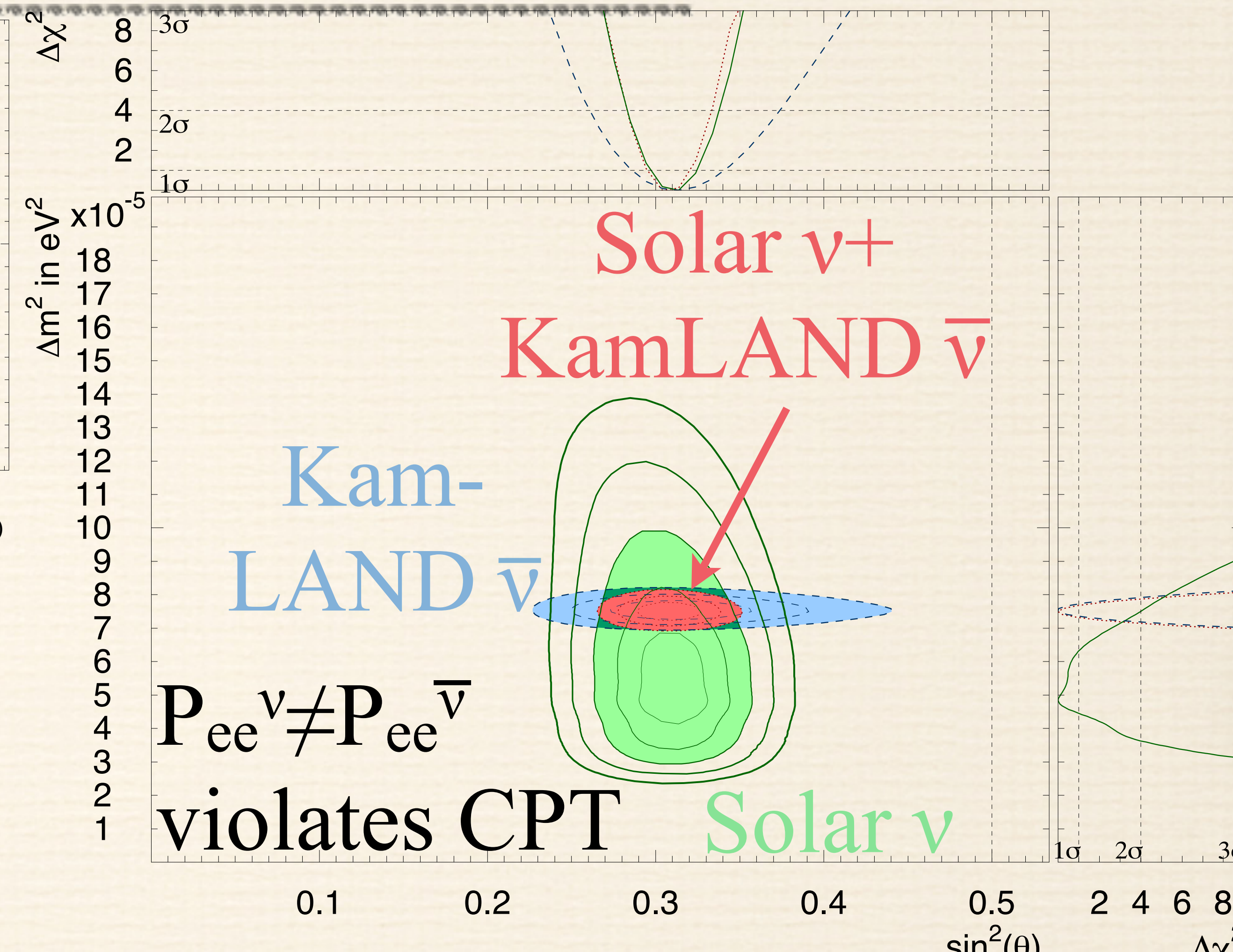


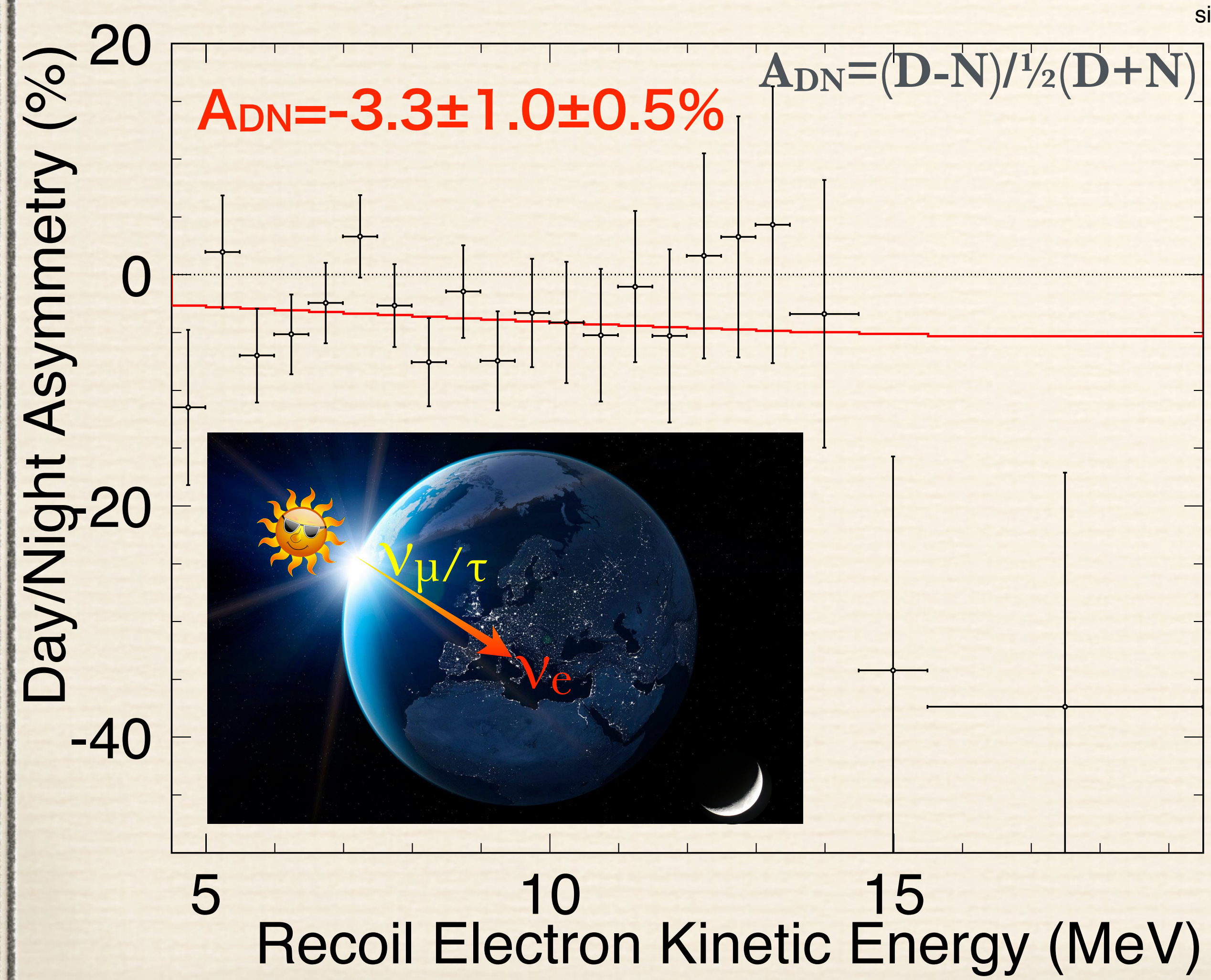
- flux
- energy spectrum
- day/night flux asymmetry
- time variation; correlation with solar activity

Oscillation and Day/Night

- best determines solar Δm^2 (via d/n effect)
- contributes significantly to solar angle determination







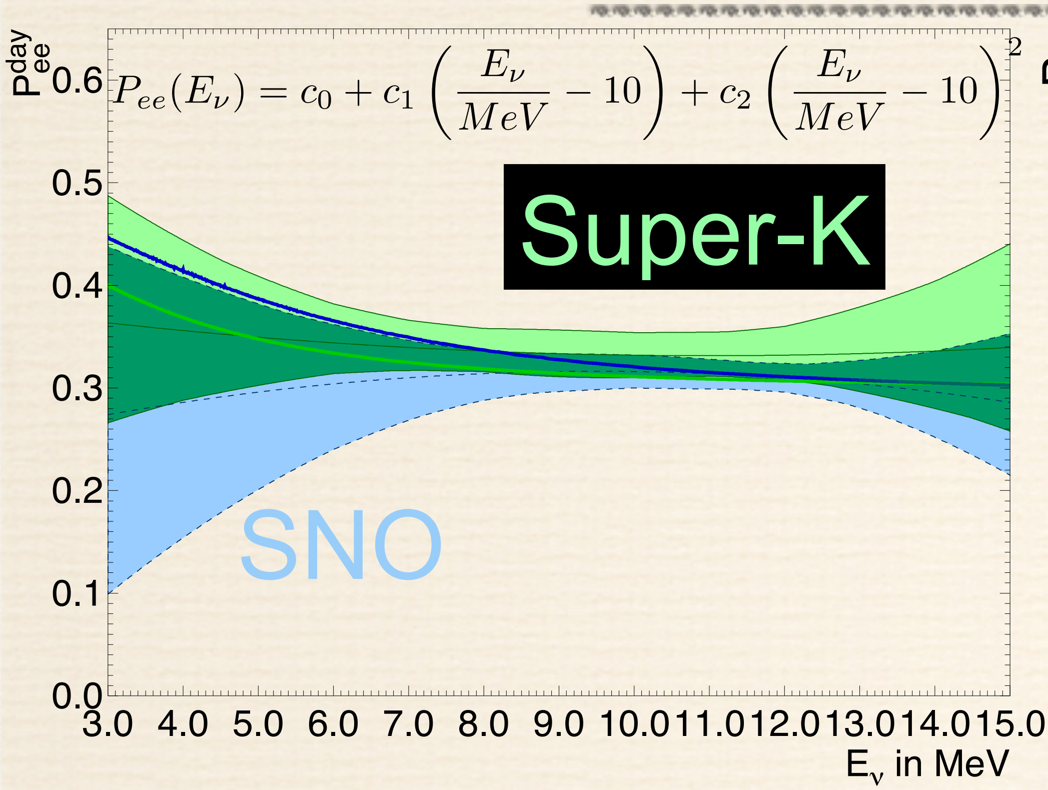
$\sin^2\theta_{13}=0.0242\pm0.0026$ (reactor)

$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$ $\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$ x10^{-5}eV^2

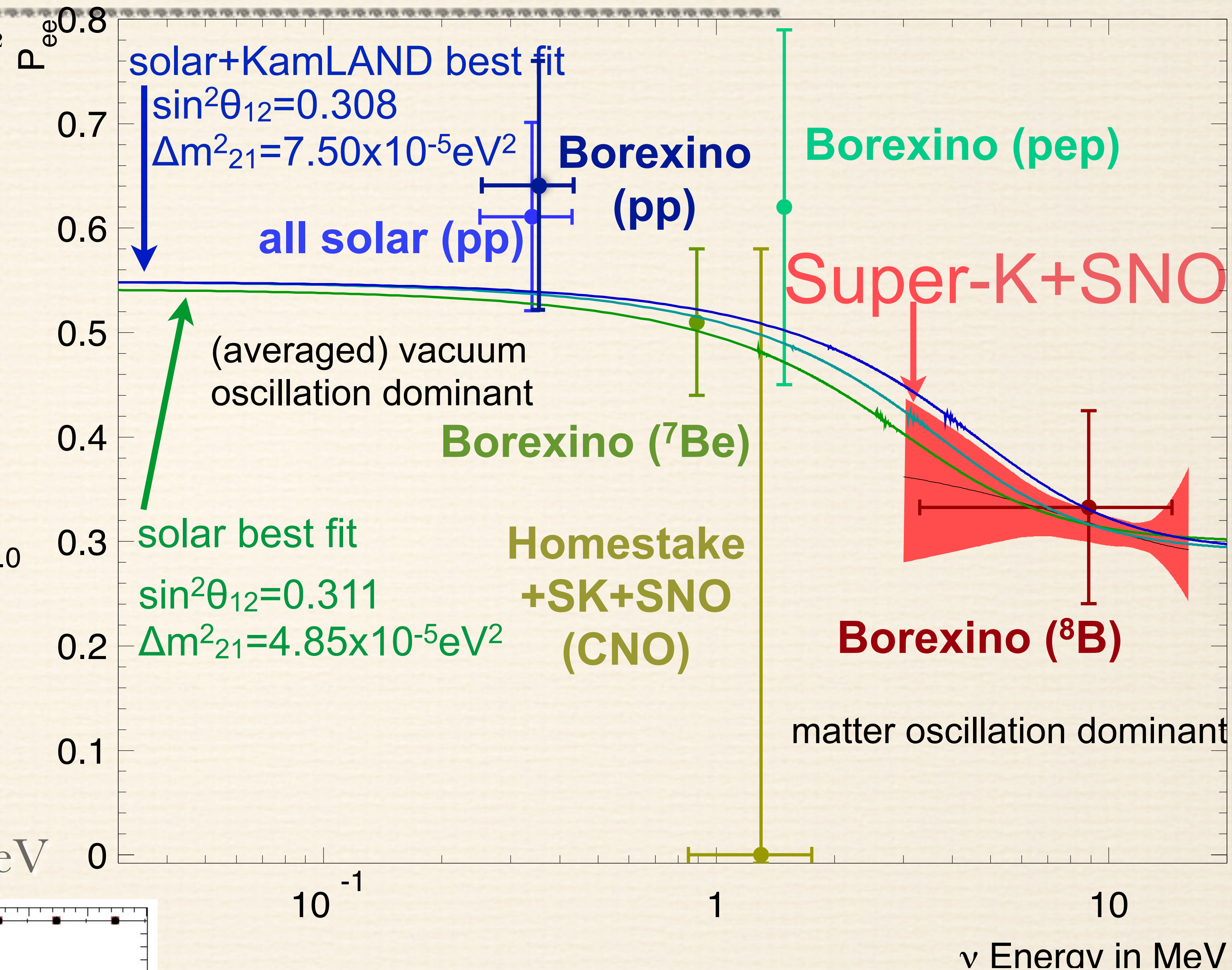
$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$ $\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$ x10^{-5}eV^2

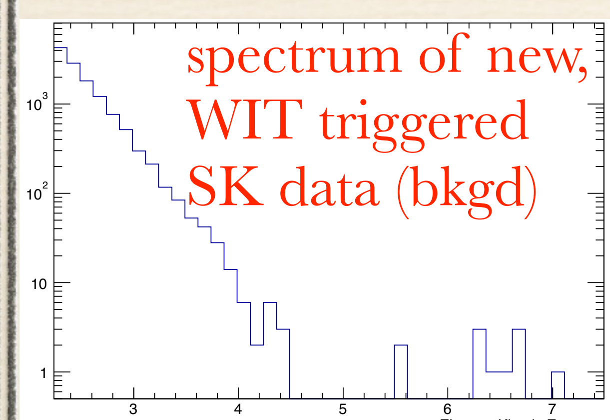
$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$ $\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$ x10^{-5}eV^2

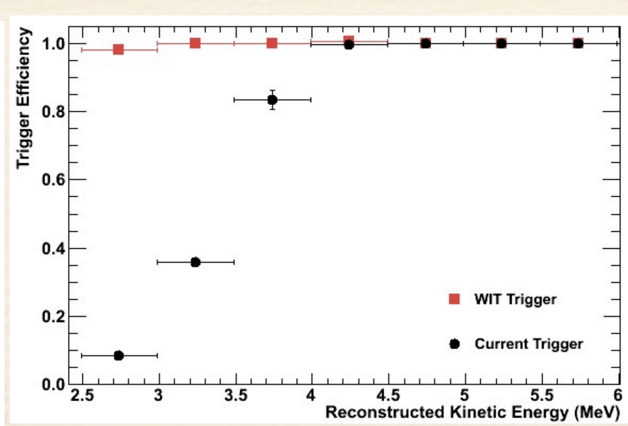
MSW Resonance



- extract survival probability as a function of neutrino energy from recoil electron spectrum
- SK: more precise below 7.5 MeV
- SNO: more precise above 11.5 MeV



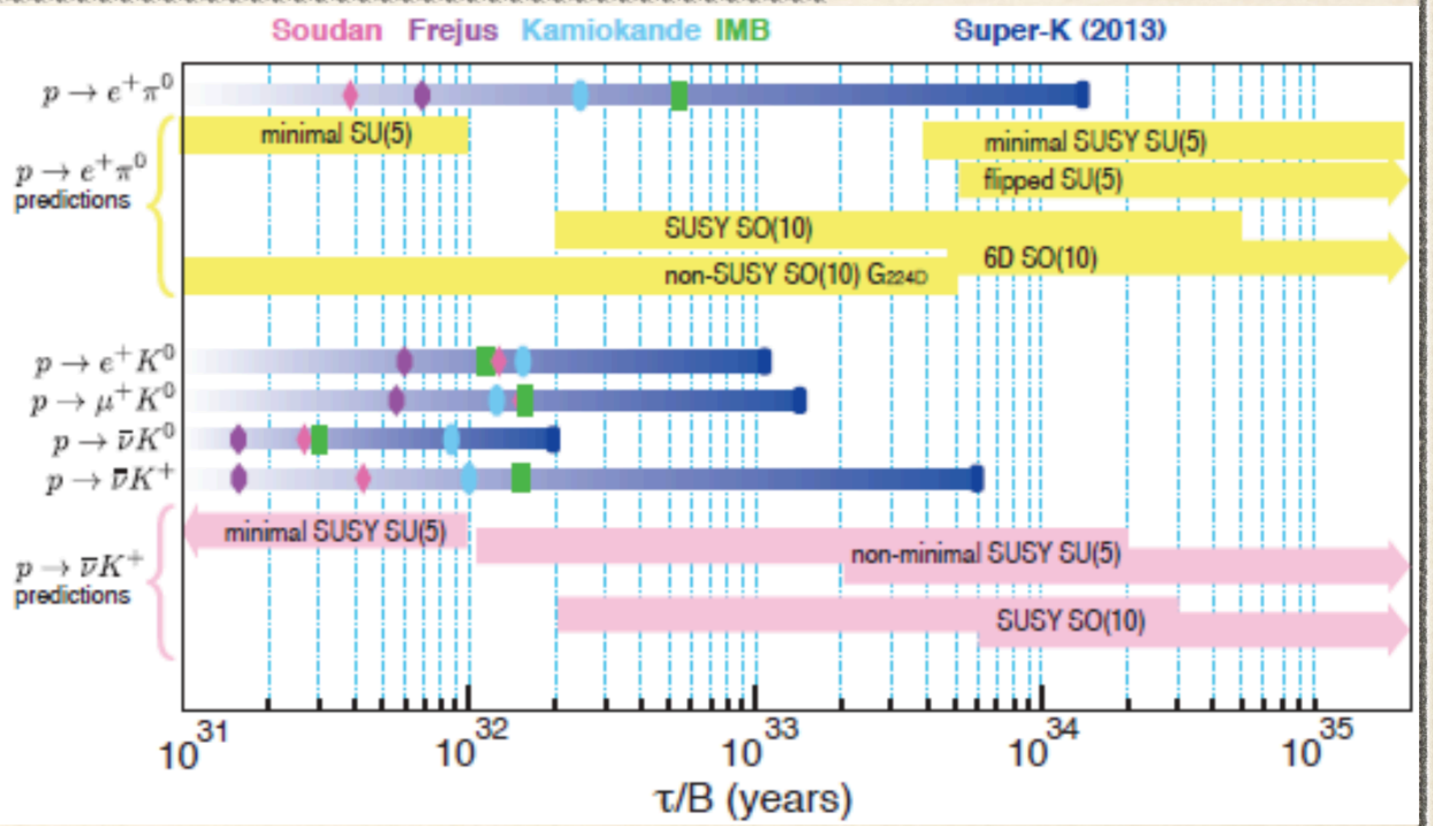


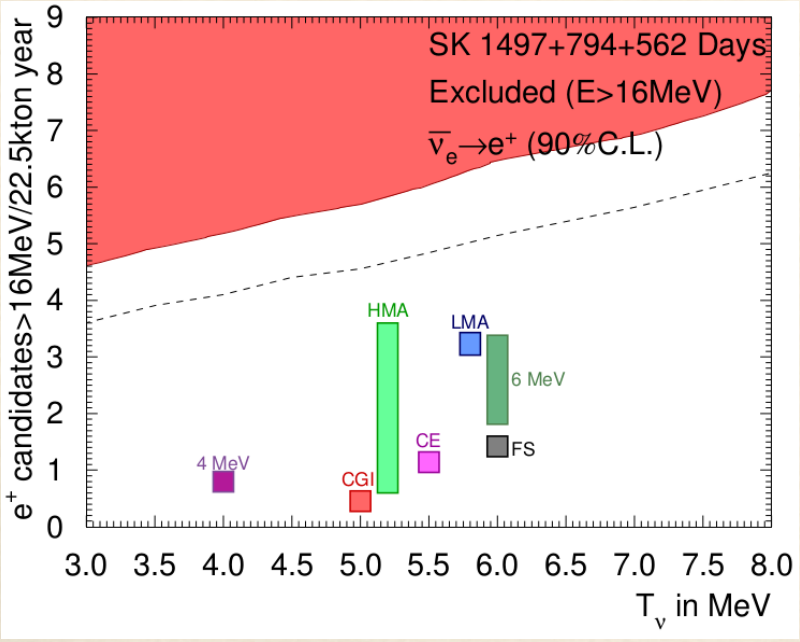


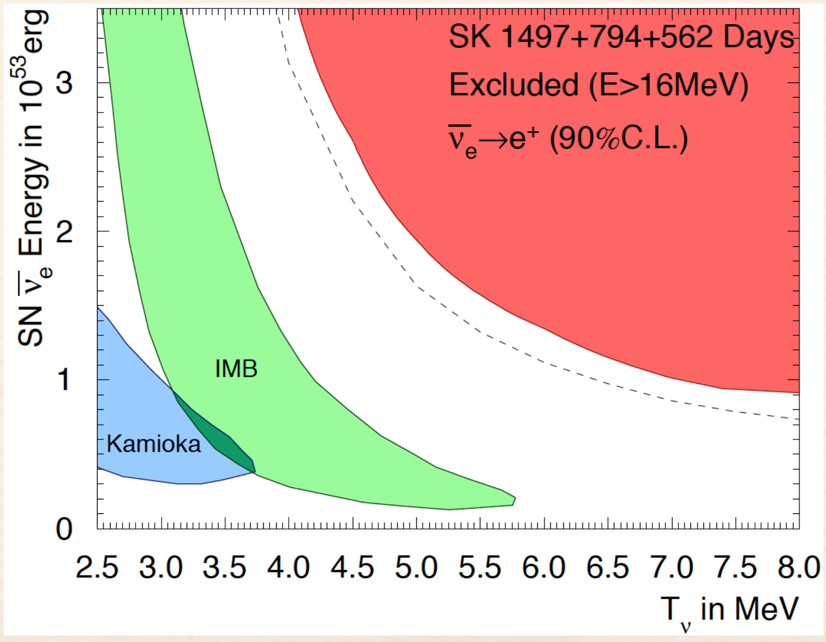
- ^{8}B is the best way to test MSW resonance
- only SK and SNO have small enough uncertainties to probe the energy dependence

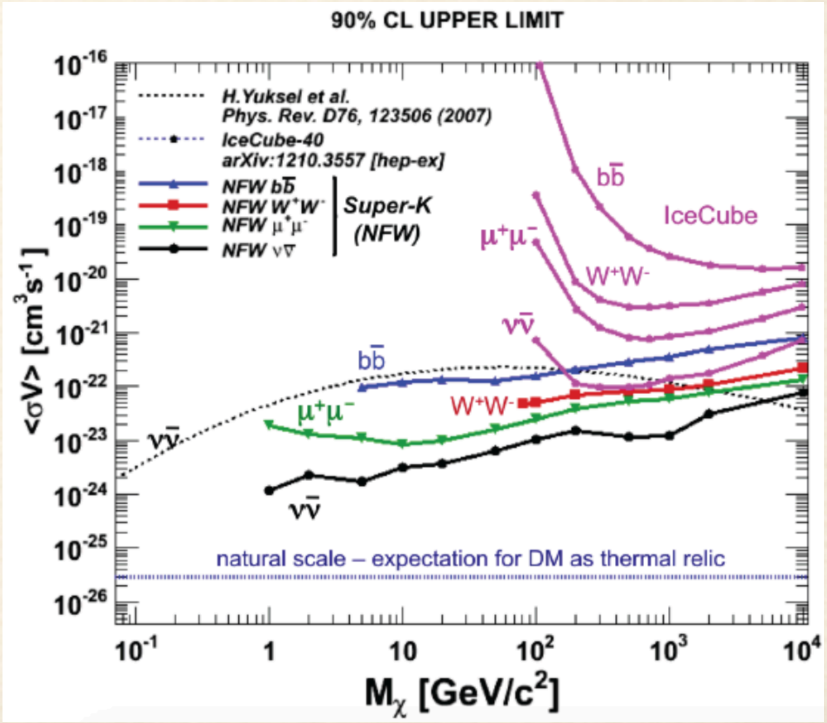
Other Physics

- search for proton decay (best limits in the world)
- search for WIMPs (indirect)
- galactic supernova burst (10kpc: ~7,300 inverse β's, 300 ES, point to SN with ~5^0)
- search for distant supernova ν's





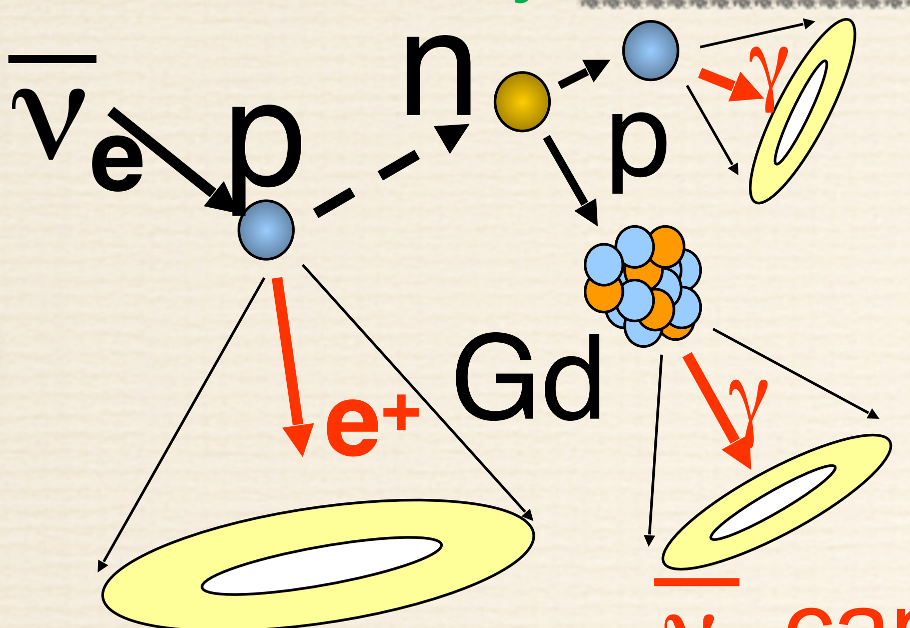




[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004].

GADZOOKS!

add 0.2% by mass of water soluble Gd compound to Super-K



Possibility 1: ≤10%

n+p→d + γ

2.2 MeV γ-ray

Possibility 2: ≥90%

n+Gd →~8 MeV γ

ΔT = ~30 μsec

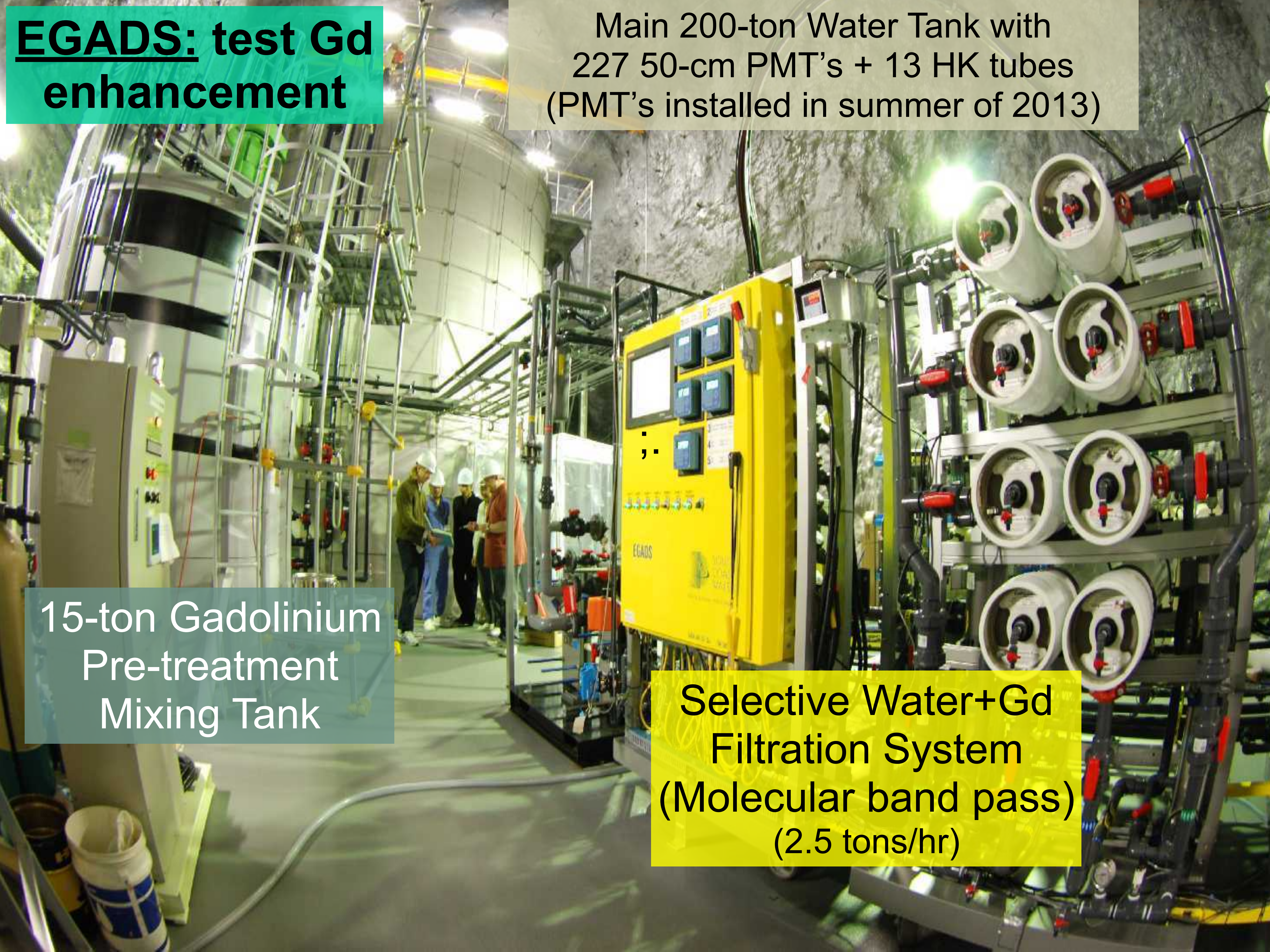
Positron and gamma ray vertices within ~50cm.

$\bar{\nu}_e$ can be identified by delayed coincidence.

Adding gadolinium to Super-K's water would make neutrons visible, allowing:

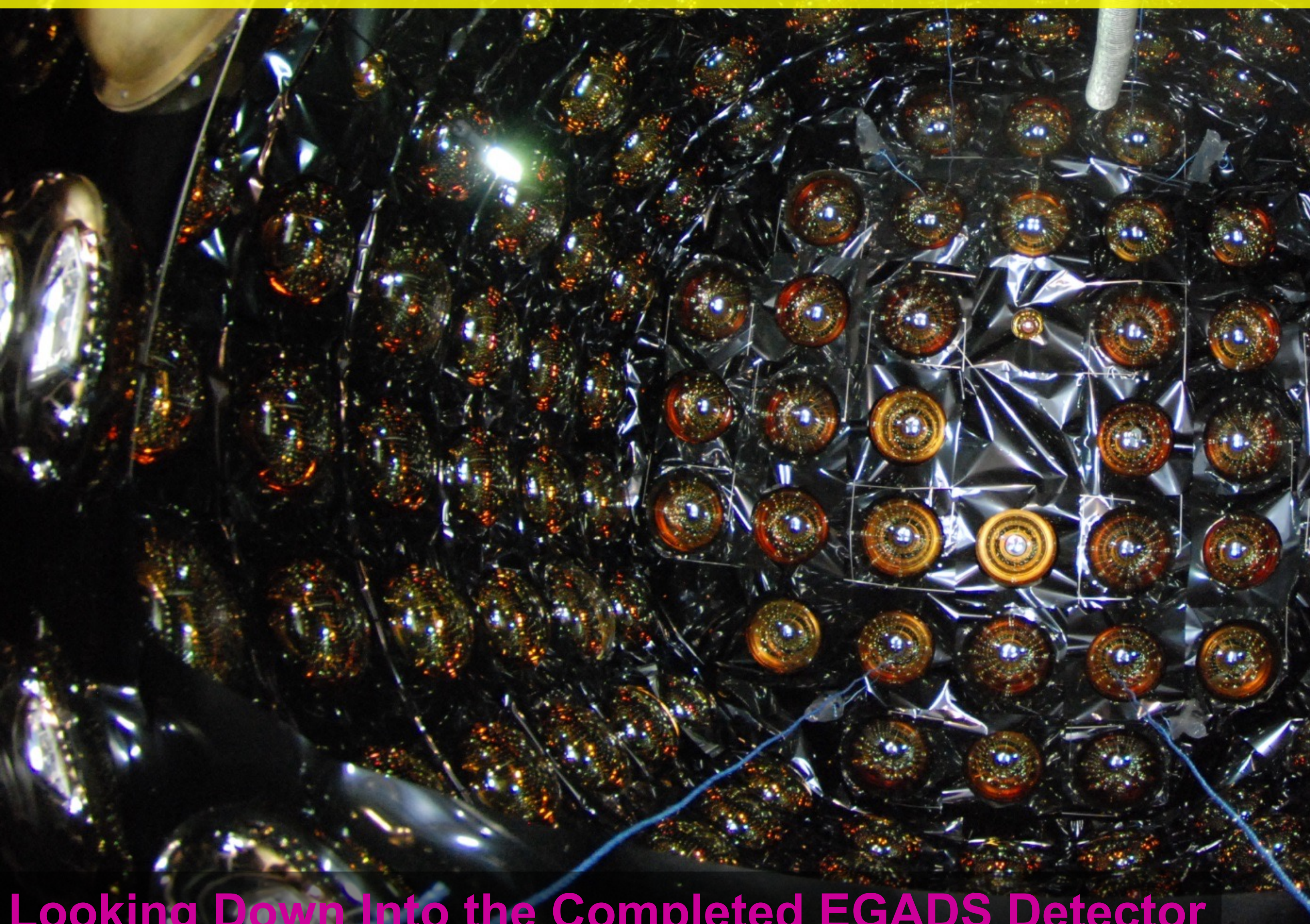
- **Rapid discovery & measurement of the diffuse supernova ν flux**
  →determine total and average SN ν energy, rate of optically failed SN
- **High statistics measurement of the ν's from nuclear power reactors**
  → greatly improved precision of Δm^2_{12}
- **De-convolution of a galactic SN's ν signals → 2X pointing accuracy**
- **Sensitivity to very late-time black hole formation following a galactic SN**
- **Early warning of SN ν burst (up to one week) from Si fusion**
- **Proton decay bkgd reduction → about 5X, vital for future searches**

EGADS: test Gd enhancement

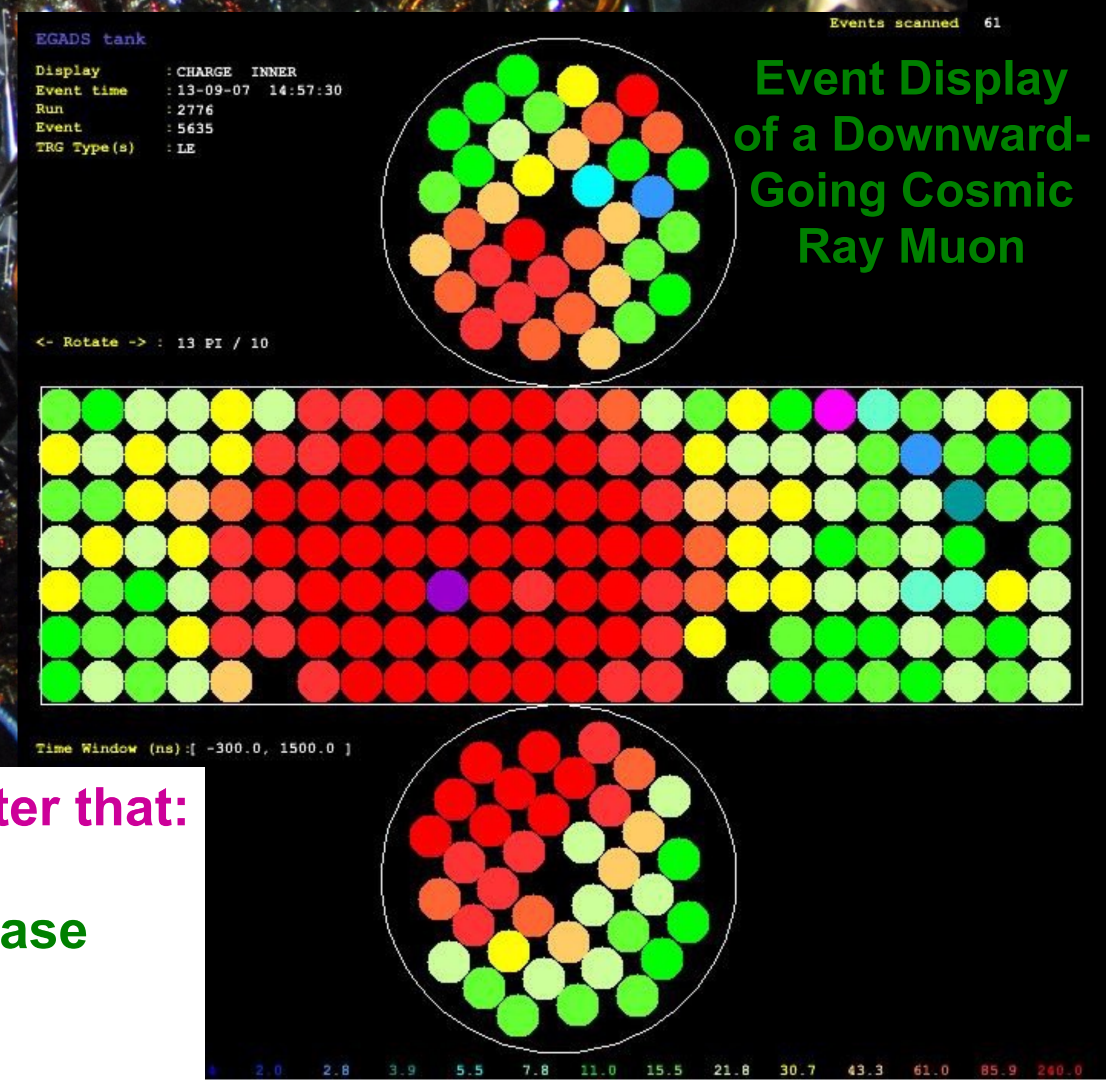


Early this year EGADS will have provided the final demonstration that gadolinium loading of Super-Kamiokande is safe and effective.

Total cost of Super-K Gd upgrade = ~ 10 million USD
Total hoped-for DOE contribution = ~1 million USD
Timescale = next three years for hardware, after that for physics



Looking Down Into the Completed EGADS Detector

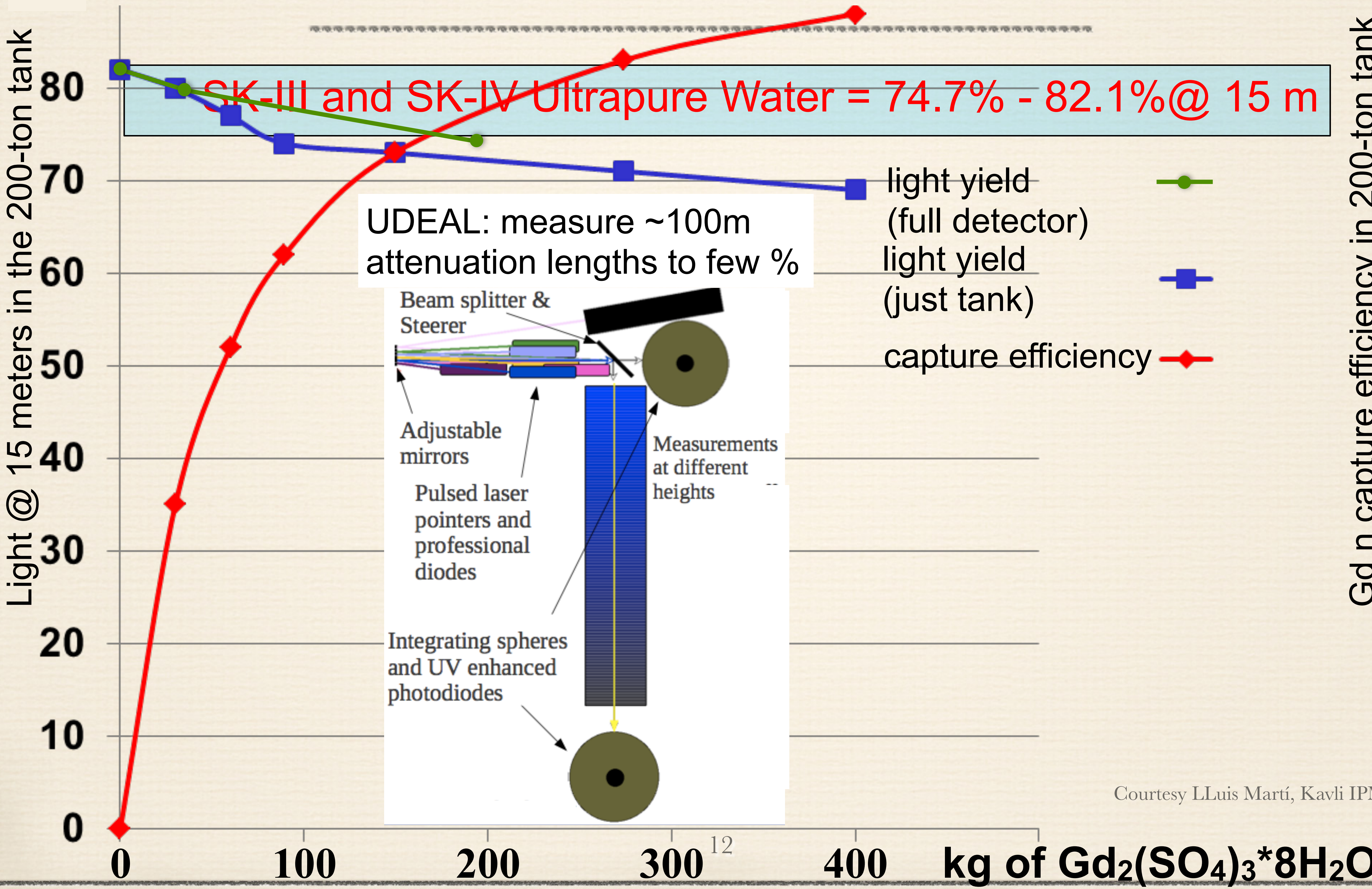


Event Display of a Downward-Going Cosmic Ray Muon

By April 2015 test results should be finalized. The likely path after that:

~June 2015 = Formal go/no go decision for Gd in Super-K
~Spring 2016 = Hardware upgrade of Super-K for gadolinium phase
~2017 = First Gd in Super-K
~2018 and beyond = Physics running with Gd

Light Yield and n Capture Efficiency



Courtesy LLuis Martí, Kavli IPMU

Super-Kamiokande Readiness

- detector ran continuously since 2006; soon it requires maintenance
- need to fix small leak for “Gadolinium”-readiness
- outer detector is U.S. responsibility
- approximately ~200/1,885 outer detector PMTs need to be replaced
- Tyvek needs to be replaced
- total cost is about ~$500,000

Super-Kamiokande Readiness

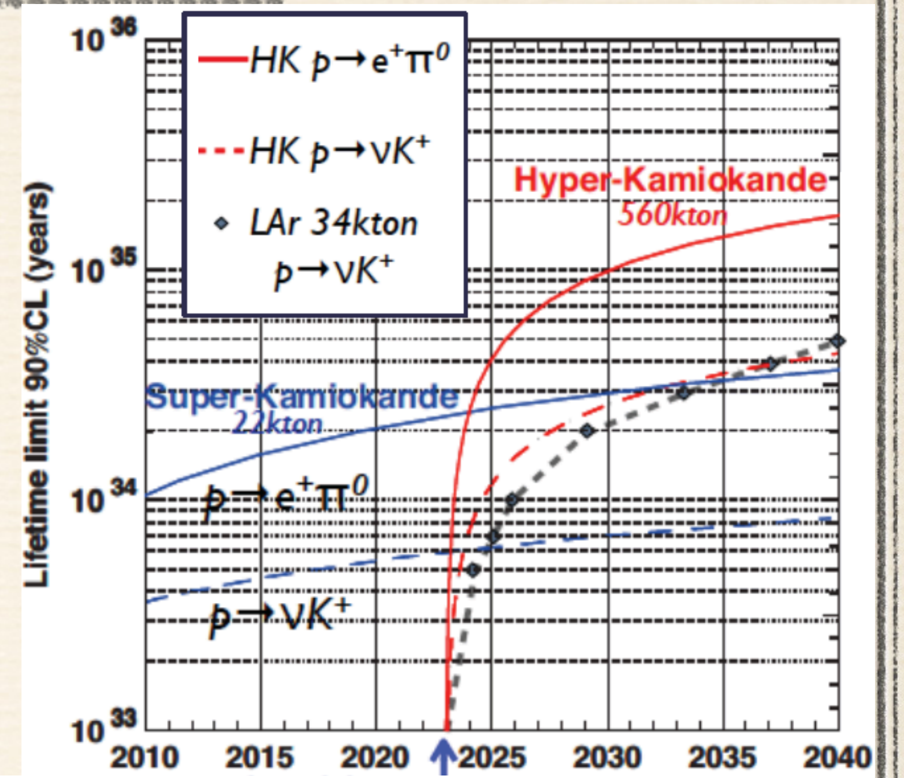
- outer detector needs also a new HV system (current old HV supplies unsupported)
- already received \$25,000
- need about \$100,000

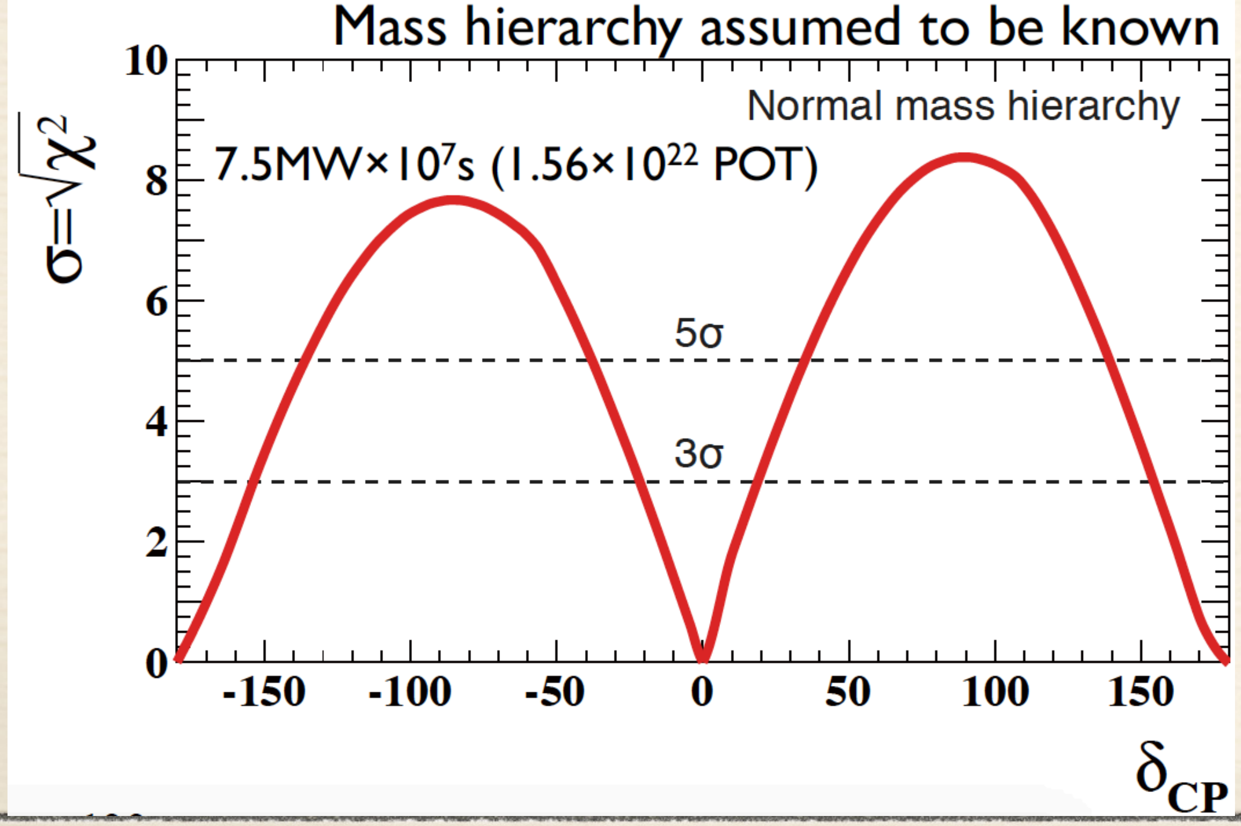
Hyper-Kamiokande

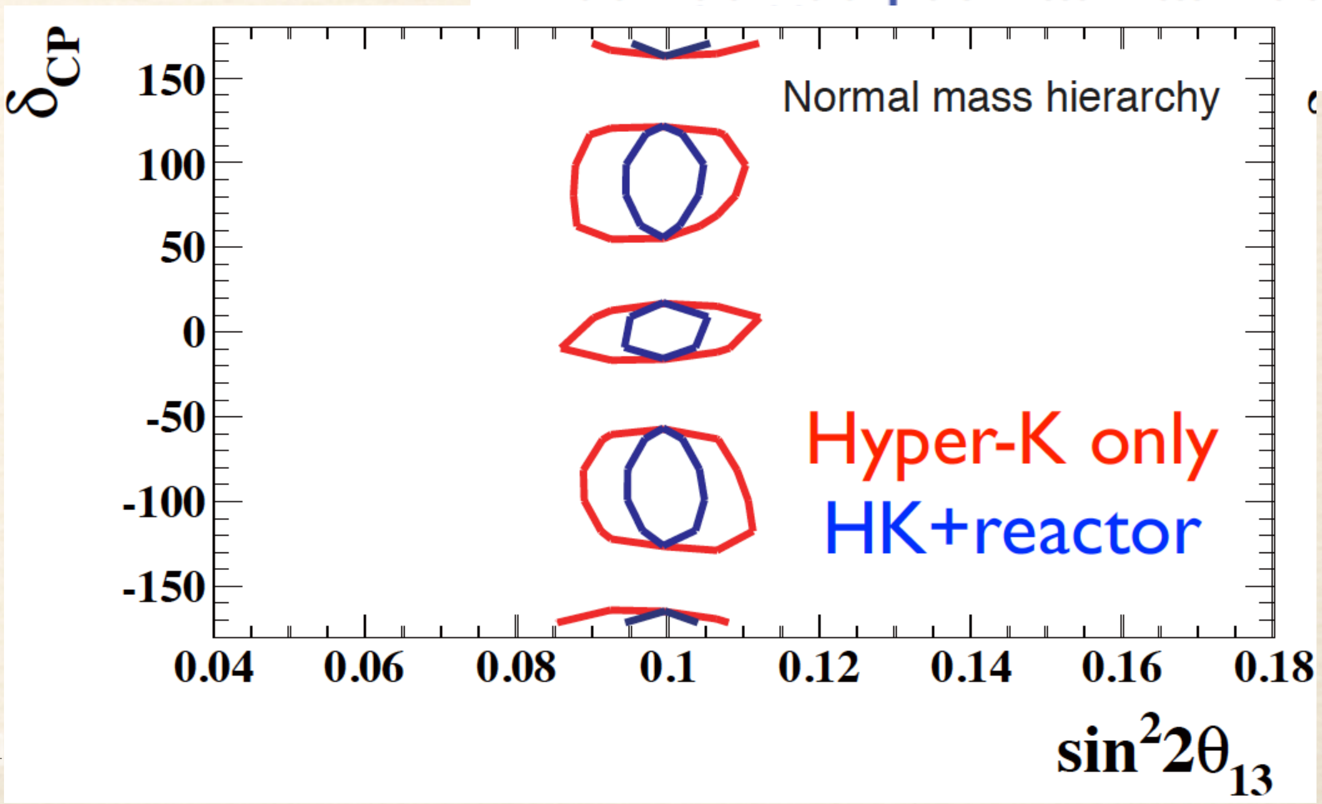
- 560 kton (fiducial) water Cherenkov detector
- launch of proto-collaboration 1 week ago
- MoU between ICRR and KEK to promote Hyper-K
- design report to be prepared within this year
- start budget request:
  - master plan 2017 → roadmap 2017
- start construction 2018 → start operation in ~2025

Hyper-Kamiokande Physics

- 10 x larger nucleon decay sensitivity than Super-K!
  - $p \rightarrow e^+\pi^0$: 5.7×10^{34} years (3σ coverage)
  - $p \rightarrow \nu K^+$: 1.2×10^{34} years (3σ coverage)
- search for neutrino CP violation with J-PARC long baseline neutrino beam
  - 76% coverage of δ_{CP} at 3σ

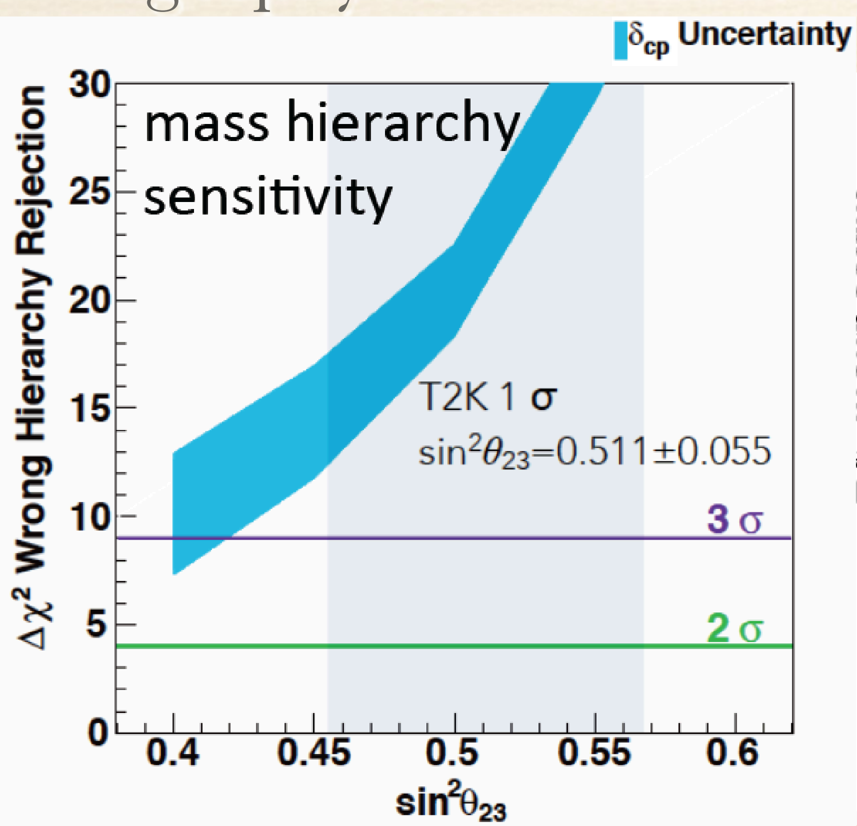


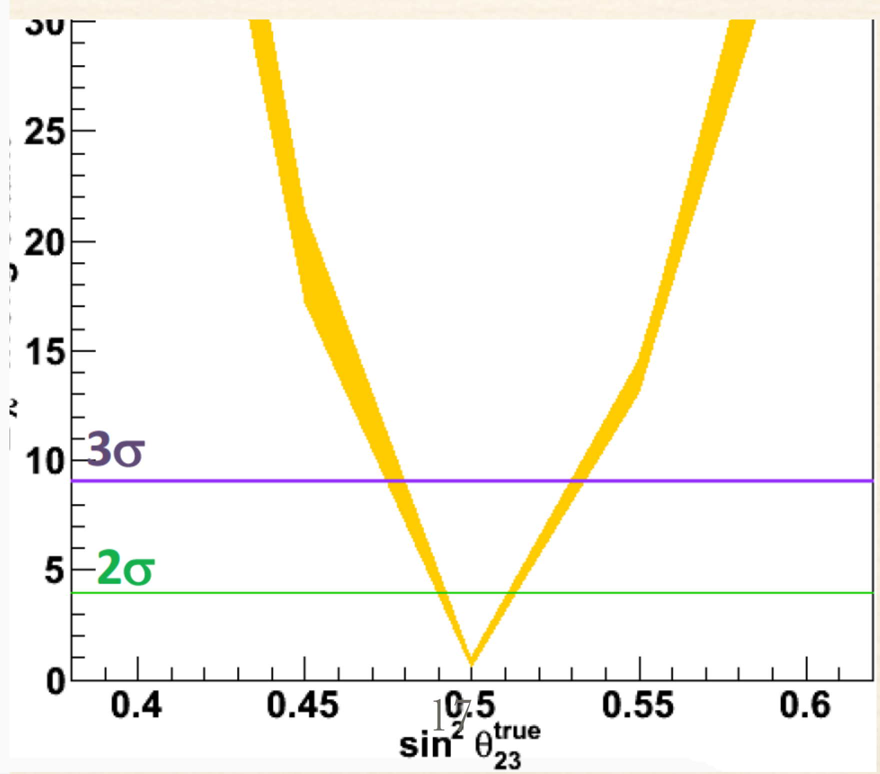


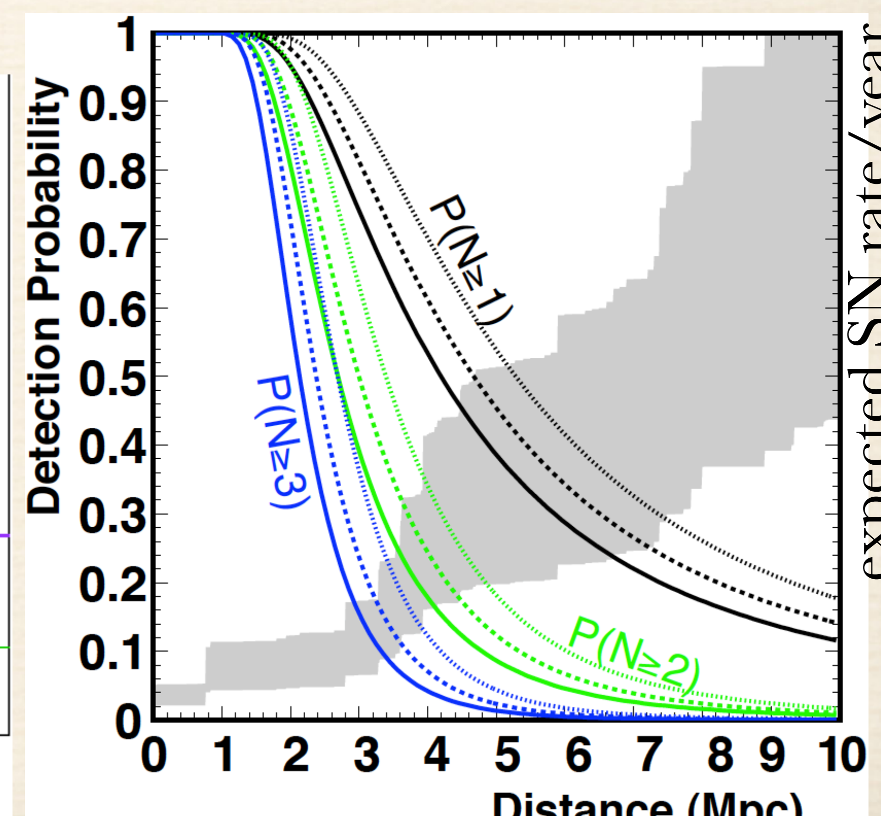


Hyper-Kamiokande Physics

- atmospheric neutrinos
  - resolve mass hierarchy and θ_{23} octant
- neutrino astrophysics
  - 200,000 neutrino interactions for GC supernova; detect bursts up to 2Mpc with 50% efficiency
  - solar neutrinos (day/night), distant SN neutrinos (830 neutrinos in 10 years)
- geophysics with neutrinos???

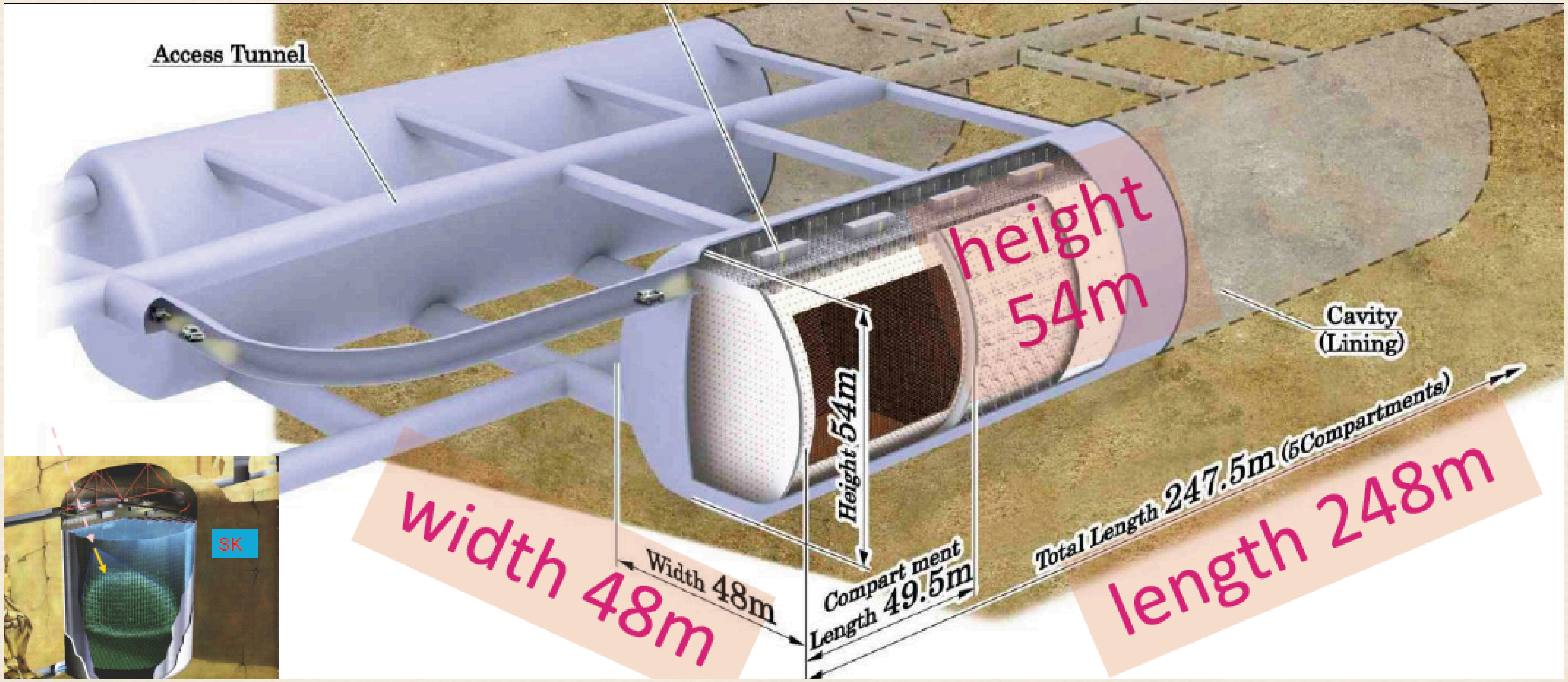




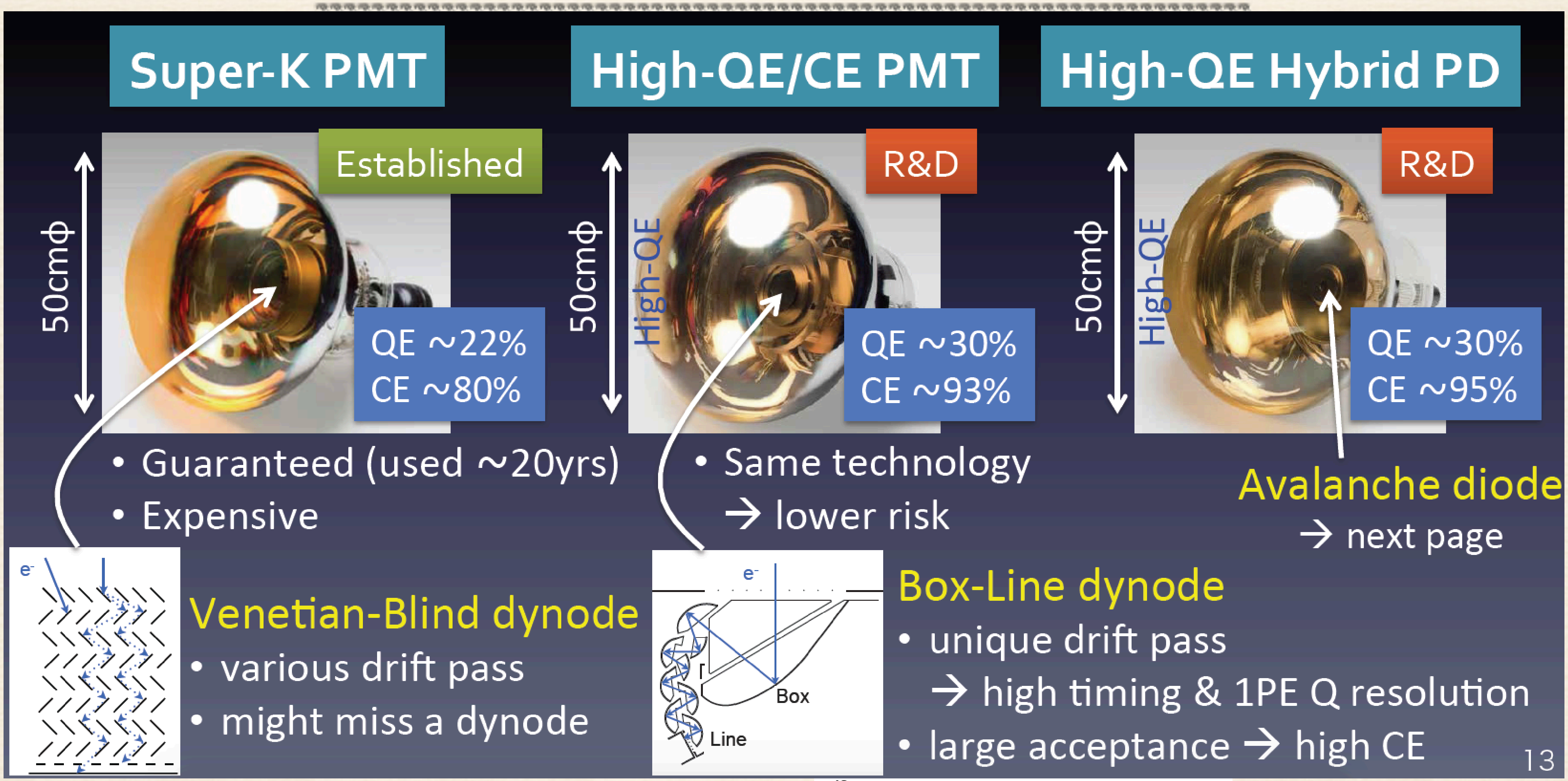


Detector Design

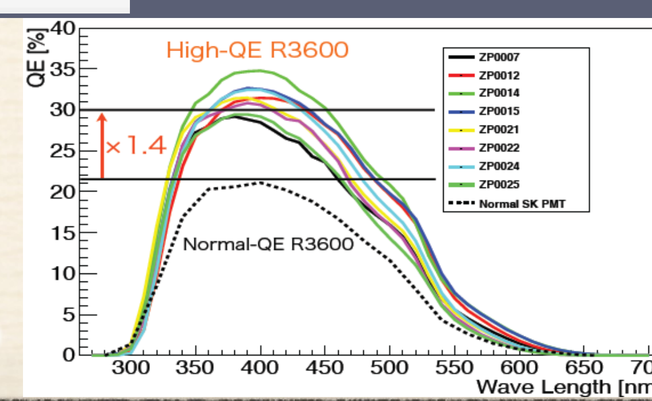
- baseline: 2x48m(W)x54m(H)x250m(L) (egg-shape cross section; 10 compartments of 56kton)
- baseline: ~99,000 inner detector 50cm PMTs (20% coverage), 25,000 veto detector 20cm PMTs (~1%)
- two options explored for the detector location

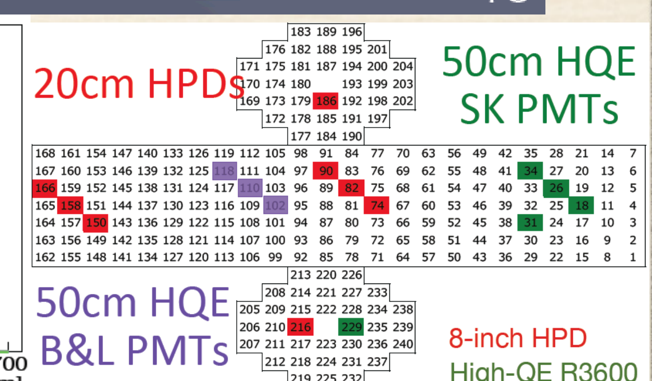


Photosensors



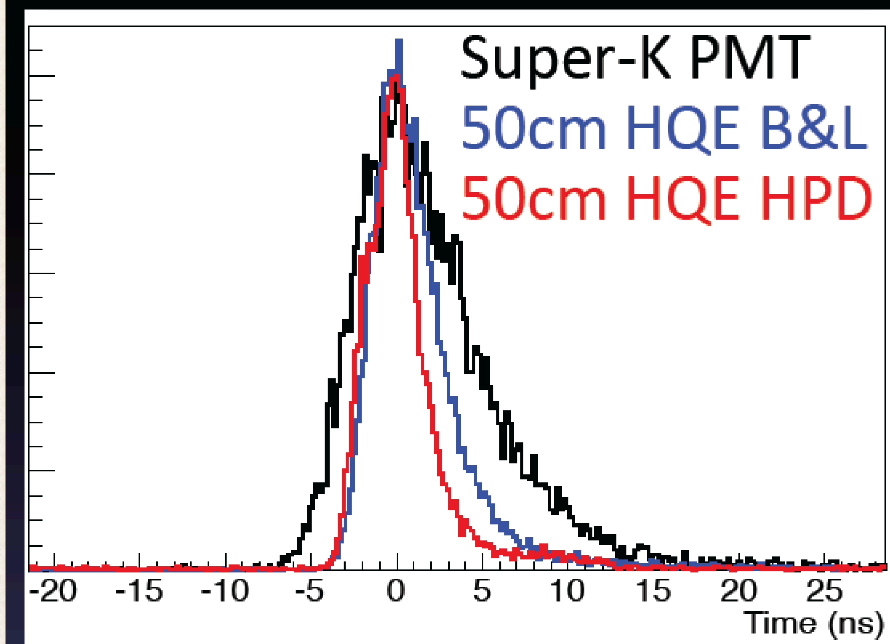
- three options considered
- tested in EGADS facility



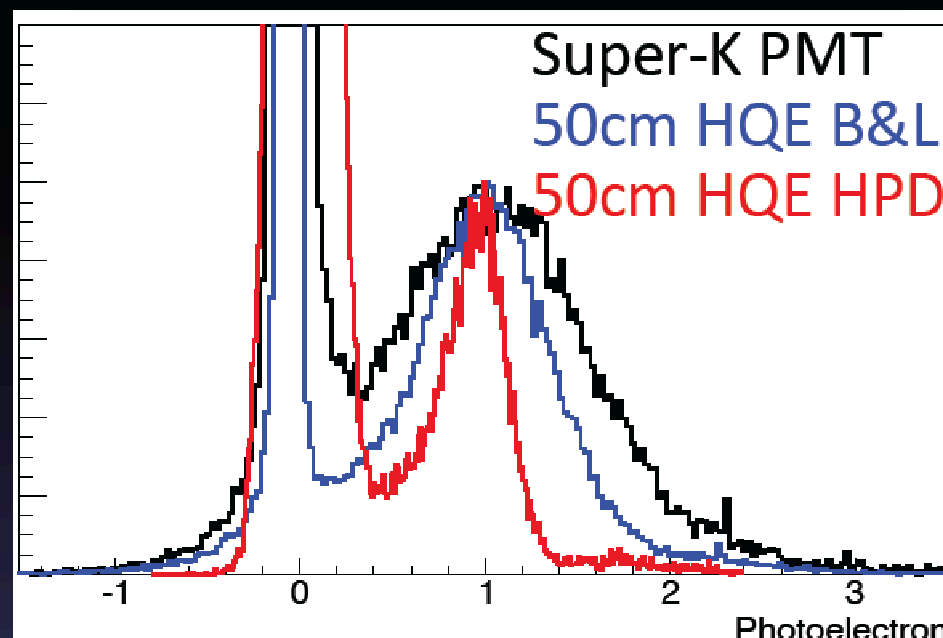


50cm Diameter PD Performance

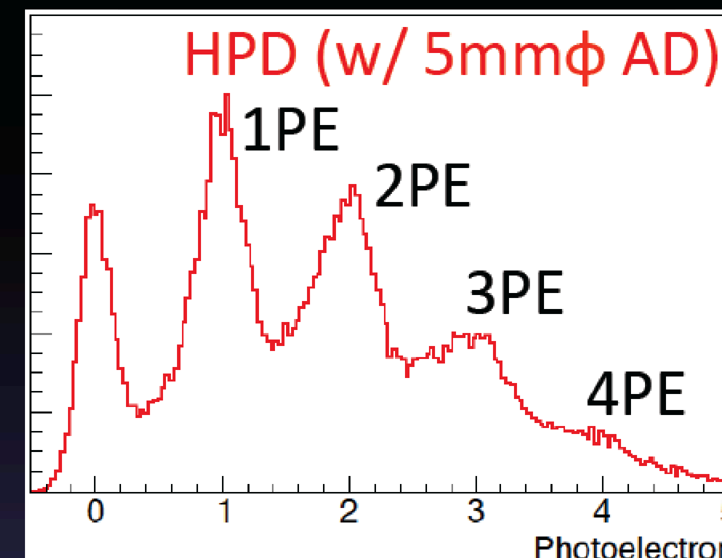
1PE timing distribution

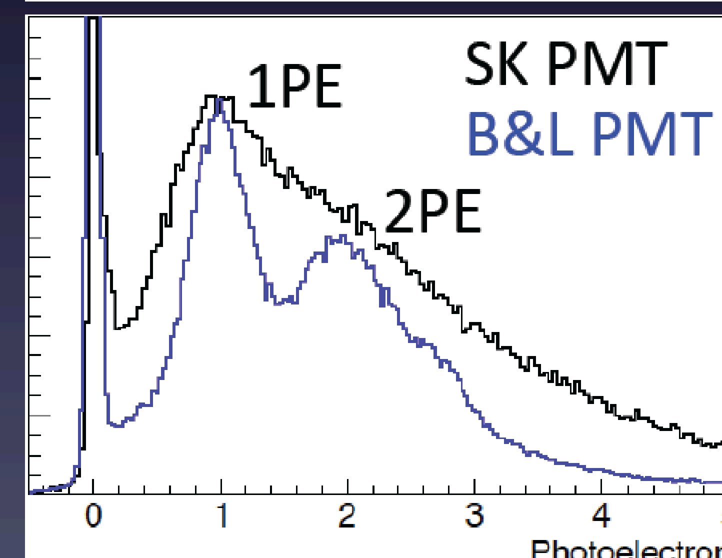


1PE charge distribution



Multi-PE peaks





	SK PMT	B&L PMT	50cm HPD (20cm)
1PE T resolution σ (ns)	2.1	1.1	1.4 (1.1)
FWHM (ns)	7.3	4.1	3.4 (3.3)
1PE Q resolution σ/mean	53%	35%	16% (12%)
Peak-to-Valley ratio	2.2	4.3	3.9 (5.2)

Much better performance than SK PMTs.

Multi-PE peaks clearly

US Plan for Hyper-Kamiokande

Possible US Contributions to Hyper-Kamiokande:

- outer detector PMT & electronics
- Gd capable water system (developed in the U.S.)
- calibration system (e.g. DT generators)

Summary

- Super-K is still doing cutting-edge neutrino measurements
- Super-K is getting ready to add Gd
- Super-K is also the far detector of T2K
- investment in Hyper-Kamiokande, the next generation of water Cherenkov detectors